Chapter 10
Saline and Sodic Soils

Abstract According to different estimates, there are 831 to 932 million hectares of salt affected soils – saline soils, saline-sodic soils and sodic soils. The measure of salinity is the electrical conductivity of the saturation extract (EC_e) and the measure of sodicity is the exchangeable sodium percentage (ESP) or the sodium adsorption ratio (SAR). Saline soils have $EC_e > 4$ dS m^{-1} (decisiemens per meter) at 25° C and ESP < 15 (high soluble salts and low exchangeable Na^+). Sodic soils have $EC_e < 4$ dS m^{-1} and ESP > 15 (low soluble salts and high exchangeable Na^+). Saline-sodic soils are characterized by $EC_e > 4$ dS m^{-1} and ESP > 15 (both salts and exchangeable sodium are high). These soils mainly occur in arid and semi-arid regions where precipitation to evapotranspiration ratio is low. These soils also develop in coastal regions because of the flooding of sea water, and in irrigated areas due to the rise of the groundwater table and in some impermeable soils of the humid regions due to lack of leaching. Salts adversely affect plant growth and crop yield. Crop failures are common occurrences although some plants may have some degree of tolerances. Salt tolerant crops can be grown in some low to moderately saline soils, but soil salinity may be so severe in some cases that cropping becomes impossible. Management of saline soils involves selecting salt tolerant crops, salt scraping, salt flushing, and leaching with irrigation and artificial drainage. Usually, chemical amendments are not necessary for the reclamation of saline soils, but chemical treatment is needed prior to leaching for managing sodic soils. Substances that contain soluble calcium such as gypsum and $CaCl_2$, and sulfuric acid or substances that produce sulfuric acid after application to soil such as sulfur, pyrite, ferrous sulfate, aluminium sulfate etc. are used as amendments for sodic soils. Phytoremediation of sodic soils has also been successful on some occasions.

Keywords Saline soils · Sodic soils · Saline-sodic soils · Reclamation · Salt tolerance · Salt scraping · Salt flushing · Leaching · Leaching requirement · Gypsum requirement

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10.1 Characteristics of Saline and Sodic Soils

All soils contain some soluble salts. Weathering of minerals of the parent materials is the principal source of soluble salts in soils. Another major source is sea water in coastal and estuarine regions. Other sources are atmospheric deposition, capillary rise of groundwater, seepage and irrigation water. Salts are added continuously to soils, and at the same time some salts are continuously removed from the soil system by erosion and leaching where water is available. In some cases, leaching is very low (for example, in areas with low precipitation to evapo-transpiration ratio), and soluble salts accumulate in the soil. Sometimes, a layer of salts accumulate on the surface of the soil in the form of a salt crust. A variety of soluble salts are found in soils; some of these salts provide plants with nutrients, but when they accumulate in excess amounts, they become harmful to growing plants. When salts accumulate in soils above a critical limit, they are called saline soils. Plants, unless adapted to saline environment, suffer from water stress, nutrient disorders, and toxicity if there are excess soluble salts in the root zone. Some soils contain excess exchangeable sodium ions with or without excess salts; they are called sodic soils. Sodic soils are highly dispersed and impervious, extremely alkaline in reaction, and produce deficiency of some nutrients and toxicity of others.

Soil salinity can be a natural event, or it may be anthropogenic. Many soils have been made saline by faulty water management. About 23% of the world's cultivated lands are saline and 37% are sodic (Khan and Duke 2001). Nearly half of the irrigated surface is seriously affected by secondary salinity and sodicity (Flagella et al. 2002). However, the criterion for judging soil salinity is not the amount of salts present in the soil, but it is the electrical conductivity of the saturation extract of the soil (EC_e) (US Salinity Laboratory Staff: Richards 1954). The electrical conductivity is proportional to the concentration of salts in solution and it is relatively easy to determine. Saturation extract is obtained by adding water to the soil up to its maximum water holding capacity and then drawing the soil solution under suction. If the electrical conductivity of the saturation extract (EC_e) at 25 °C is >4 dS m^{-1}, the soil is saline. The criteria of sodicity are exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR).

$$\text{ESP} = \frac{\text{Exchangeable Na}^+}{\text{CEC}} \times 100, \text{and}$$

$$\text{SAR} = \frac{Na^+}{\sqrt{\frac{1}{2}\left(Ca^{2+} + Mg^{2+}\right)}}$$

A soil is said to be sodic if the ESP exceeds 15 or the SAR is higher than 13. Thus, soils may be classified on the basis of EC_e and ESP (or SAR) into four categories (Table 10.1). Richards (1954) used the unit mmhos cm^{-1} (mho is inverse of ohm; since conductivity is inverse of resistance; the unit of resistance is ohm) for

Table 10.1 Categories of saline and sodic soils[a]

Category of soil	EC_e, dS m^{-1}	ESP Exchangeable sodium percentage (ESP)	SAR	Common name
Saline non-sodic	> 4	< 15	< 13	Saline soil
Saline sodic	> 4	> 15	>13	Saline-sodic soil
Non-saline sodic	< 4	> 15	> 13	Sodic soil
Non-saline non-sodic	< 4	< 15	< 13	Normal soil

[a]Classical classification of saline and sodic soils according to Richards (1954).

EC_e. Later, dS m^{-1} (decisiemens per meter) is used instead of mmhos cm^{-1}. Useful conversion factors are: mmhos cm^{-1} = dS m^{-1} = mS cm^{-1} = 1000 μS cm^{-1} = 1000 μmhos cm^{-1}.

However, determination of electrical conductivity of the saturation extract (EC_e) is a tedious job for some laboratories and for routine analysis. The particular problem is associated with drawing the extract under suction. There is also possibility of variable water addition to saturate the different batches of soil samples. Some investigators, therefore, used soil:water ratios of 1:1 or 1:5 and correlated with the EC_e (electrical conductivity of the saturation extract). Data of Qadir et al. (2010) are summarized below.

Pre-leaching*	**Post-leaching****	**Combined*****
$EC_e = 1.98 \times EC_{1:1}$	$EC_e = 2.16 \times EC_{1:1}$	$EC_e = 2.06 \times EC_{1:1}$
$EC_e = 6.53 \times EC_{1:5}$	$EC_e = 2.08 \times EC_{1:5}$	$EC_e = 2.42 \times EC_{1:5}$

Number of samples, *n = 75, ** n = 105 and *** n = 180; the R^2value ranged between 088 and 0.92

Such conversion factors were also proposed by other investigators, such as Shirokova et al. (2000) and Akramkhanov et al. (2008).

Saline soils

Saline soils contain sufficient neutral soluble salts that adversely affect the growth of most crop plants. The EC_e of 4 dS m^{-1} is still used as the standard for saline soils the world over, but the yield of most crop plants is reduced at this EC_e. Many crops exhibit yield reductions at much lower EC_e values (Munns 2005; Jamil et al. 2011), such as the EC_e of 1 dS m^{-1} (Chinnusamy et al. 2005). The Terminology Committee of the Soil Science Society of America has lowered the boundary between saline and non-saline soils to EC_e 2 dS m^{-1} in the saturation extract (Soil Survey Staff 1993). Table 10.2 presents a classification of saline soils on the basis of EC_e and plant responses.

Natural salts in saline soils include mainly neutral salts such as chlorides (Cl^-) and sulfates (SO_4^{2-}) of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+) although NaCl dominates. Nitrates may be present on a few occasions. Carbonates and bicarbonates are usually absent. Many saline soils contain appreciable quantities of gypsum ($CaSO_4$. $2H_2O$) lower in the profile. The pH of saline

Table 10.2 Soil salinity classes

Soil salinity class	EC_e, dS m^{-1}	Effect on crop plants
Nonsaline	0–2	Salinity effects negligible
Slightly saline	2–4	Yield of sensitive crops may be restricted
Moderately saline	4–8	Yield of many crops are restricted
Strongly saline	8–16	Only tolerant crops yield satisfactorily
Very strongly saline	>16	Only a few tolerant crops yield satisfactorily

Source: http://www2.vernier.com/sample_labs/AWV-09-COMP-soil_salinity.pdf

soils (saturated paste) remains near neutrality but may be as high as 8.2–8.5. Saline soils have good soil structure because excess salts keep the clay particles in flocculated state. Flocculation helps particles cling together and initiate their binding into aggregates.

Saline soils generally have good physical properties; they are usually porous and permeable. Leaching these soils with low-salinity water, tend to disperse fine textured saline soils resulting in low permeability to water and air. Spotty growth of crops, burning of leaves, and white salt crusts are field indicators of soil salinity. Barren spots and stunted plants may appear in cereal or forage crops growing on saline areas.

Saline-Sodic Soils

Saline-sodic soils have electrical conductivity of the saturation extract >4 dS m^{-1} and exchangeable sodium percentage level > 15 percent. The pH values of these soils are usually less than 8.2. These soils have both excess soluble salts and excess exchangeable sodium. The dominant salts in saline–sodic soils are chlorides and sulfates of sodium, calcium and magnesium along with carbonates and bicarbonates. The physical conditions of these soils are good as long as there are high salt levels. High concentration of salts keeps the colloids flocculated and well aggregated. Leaching of salts may cause dispersion and accompanied degradation of soil structure and loss of water permeability.

Sodic soils

Sodic (non-saline) soils contain high proportion of exchangeable sodium (more than 15 percent) in colloidal surfaces which keep the particles dispersed and prevent them from binding into aggregates. So, excess exchangeable sodium has an adverse effect on physical, chemical and nutritional properties of soil. A dense layer of clay occurs at or near the surface of sodic soils. This layer, often called a clay pan, is a root restrictive layer. Many soils of ESP > 15 (or SAR > 13) have very poor soil physical properties which are unsuitable for crop growth. Contents of neutral salts are low; the salts present in sodic soils are capable of undergoing alkaline hydrolysis. Carbonates and bicarbonates of Na^+, Ca^{2+} and Mg^{2+} predominate. The electrical conductivity of saturation extracts is less than 4 dS m^{-1} at 25 °C. The pH of saturated soil paste is higher than 8.2; in some cases, it can be as high as 10.5. Dispersed and dissolved organic matter present in the soil solution of some highly sodic soils gives them a dark color for which these soils were earlier called black alkali soils.

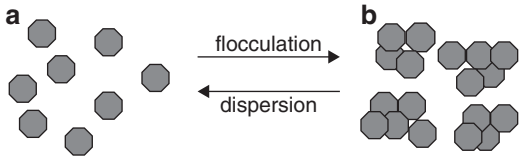


Fig. 10.1 Schematic representation of dispersion (**a**) and flocculation (**b**)

The dispersion of clay particles creates poor soil structure, and these soils are impervious and of low hydraulic conductivity. The reversible processes of dispersion and flocculation are shown in Fig. 10.1.

The total salt concentrations in sodic soils could be low or high, but the concept of sodicity is based on the high ratio of Na^+ to Ca^{2+} and Mg^{2+}. Both ESP and SAR are some forms of expression of this ratio, but the USDA Soil Salinity Laboratory criterion of ESP >15 for sodic soils is not followed universally. It has become controversial for large scale variability in sodicity levels across continents and occurrence of dispersion at variable ESP levels (Gregory and Nortcliff 2013). ESP >15% is still followed in the USA, but in Australia, an ESP of 6 is the limit. Sometimes, dispersion can even occur in ESP values <1.

The principal cause of alkaline reaction of sodic soils is the hydrolysis of either the exchangeable cations or of such salts as $CaCO_3$, $MgCO_3$, Na_2CO_3, etc. Hydrolysis of the exchangeable cations takes place according to the following reactions:

$$\text{Na-clay-Na} + \text{H}_2\text{O} \leftrightarrow \text{Na-clay-H} + \text{Na}^+ + \text{OH}^-$$

The displaced Na does not combine with, or inactivate OH^- ions, which results in an increase in the OH^- ion concentration and increased soil pH. Hydrolysis of compounds like $CaCO_3$, and $MgCO_3$ takes place according to the following reaction:

$$\text{CaCO}_3 + 2\text{H}_2\text{O} \Leftrightarrow \text{Ca}^{2+} + 2\text{OH}^- + \text{H}_2\text{CO}_3$$

Here H^+ is inactivated through combination with carbonate to form weakly ionized carbonic acid. Hydrolysis of $CaCO_3$ and of $MgCO_3$ is limited in soil due to their low solubility, and, therefore, they tend to produce a pH in soils no higher than about 8.0–8.2. Soils containing excess Na_2CO_3 have a pH greater than 8.2 and as high as 10.5. This is due to the higher solubility of Na_2CO_3. Major distinctions between saline and sodic soils are shown in Table 10.3.

10.2 Development of Salinity and Sodicity in Soils

There are natural and anthropogenic causes of soil salinity development. Natural causes include low or insufficient leaching due to aridity, parent materials of the soils, shallow groundwater table high in salts, saline seepage, capillary rise of water

Table 10.3 Major distinguishing characteristics of saline and sodic soils

Characteristics	Saline soils	Sodic soils
Chemical	(a) There are neutral salts consisting of chlorides and sulfates of sodium, calcium and magnesium. (b) the pH of saturated soil paste is less than 8.2. (c) an electrical conductivity of the saturated soil extract is >4 dS m^{-1} at 25 °C. (d) There is no well-defined relationship between pH and ESP. (e). Soils may contain significant quantities of sparingly soluble calcium compounds, e.g. gypsum.	(a) Neutral salts are generally absent. Appreciable quantities of salts capable of alkaline hydrolysis, e.g. Na_2CO_3, present. (b) the pH of the saturated soil paste is more than 8.2. (c) ESP > 15; electrical conductivity of the saturated soil extract <4 dS m^{-1} at 25 °C but may be more if appreciable quantities of Na_2CO_3 etc. are present. (d) the pH and ESP are related. (e) Sodium is the dominant soluble cation. High pH of the soils results in precipitation of soluble ca and mg such that their concentration in the soil solution is very low. (f) Gypsum is nearly always absent in such soils.
Physical	(a) for excess soluble salts the clay fraction is flocculated, and the soils have a good structure. (b) Permeability of soils to water and air is good.	(a) Excess exchangeable sodium causes dispersion of clay and poor soil structure. (b) Permeability of soils to water and air is restricted. .
Effect on plant growth	In saline soils plant growth is adversely affected: (a) Chiefly through the effect of excess salts on the osmotic pressure of soil solution resulting in reduced availability of water; (b) through toxicity of specific ions, e.g. Na, cl, B, etc.	In sodic soils plant growth is adversely affected: (a) Chiefly through the dispersive effect of excess exchangeable sodium resulting in poor physical properties; (b) through the effect of high soil pH on nutritional imbalances including a deficiency of calcium; (c) through toxicity of specific ions, e.g. Na, CO_3, Mo, etc.
Soil improvement	Improvement of saline soils essentially requires the removal of soluble salts in the root zone through leaching and drainage.	Chemical amendments followed by leaching, irrigation and drainage are needed.

due to dryness in the surface soil, coastal flooding, etc. Human induced causes are faulty irrigation system, faulty drainage system, use of saline water for irrigation, inundation with saline water for salt farming as well as shrimp farming.

It has already been mentioned that major sources of soluble salts in soils are weathering of minerals, sea water, groundwater, seepage water, irrigation water and atmospheric deposition. These salts are natural salts which mainly contain chlorides and sulfates of sodium, calcium, magnesium and potassium. If the soil is sodic, the dominant anions may be carbonates and bicarbonates and the dominant cation is sodium. There are associations of natural salt accumulations in soils with climatic regions. The most soluble salts, such as magnesium and calcium chlorides, are only

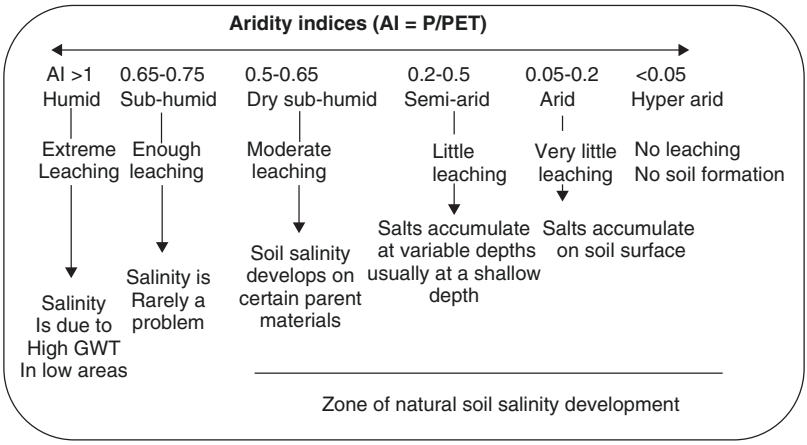


Fig. 10.2 Schematic representation of soil salinity development in arid and semi-arid lands

found under the most arid conditions; magnesium and sodium sulfates and sodium chloride are common in arid and semi-arid environments. With increasing humidity, the most soluble salts disappear and only gypsum and finally only calcium carbonate is found.

Salinity

There are two major salinization processes: natural or primary salinization and human induced or secondary salinization. Most saline soils are found in arid and semi-arid regions. As it has already been discussed, the aridity index (AI = P/PET) ranges from 0.05 to 0.65. The lower the aridity index, the lower is the availability of water for leaching soluble salts. So, at a lower aridity index, there is higher chance of accumulation of soluble salts in soil surface (Fig. 10.2).

In the arid and semiarid regions, evapotranspiration greatly exceeds precipitation, or the precipitation/evapotranspiration ratio is low. Salts released from weathering of minerals cannot be leached due to insufficient percolation. Moreover, capillary rise of water brings salts upward; water evaporates leaving the salts in the surface soil (Fig. 10.3).

Salinity also develops in soils of coastal and estuarine areas by flooding with sea water, and ponding of salt water in lagoons and depressions. In basins of humid regions, rise of the groundwater often causes soil salinity. Shallow groundwater table can contribute to the development of soil salinity in both arid and humid regions. Studies have shown that significant evaporation from soil surface can occur due to capillary rise of water from groundwater table within 1–2 m depth of soil, which contributes to the development of root zone salinity. Salinization problems can be more severe when the salinity of groundwater is high, as is usually the case in arid regions. Irrigation with salty water without enough drainage has caused salinity in many soils. In coastal regions, shrimp farmers and salt farmers pond sea water in polders in a season. These soils become highly saline in the long run.

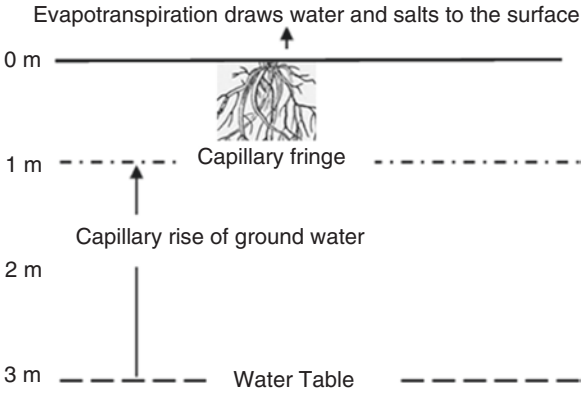


Fig. 10.3 Capillary rise of water and salts at high evapotranspiration

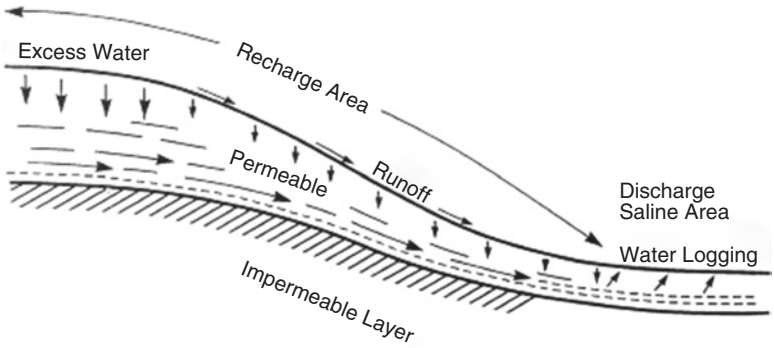


Fig. 10.4 Formation of saline soils through saline seeps

Saline seeps are a kind of dryland salinity which is widespread in Western Australia and in the Great Plains region of North America. It occurs extensively in Canada in the prairie provinces of Manitoba, Saskatchewan and Alberta and in the United States in the states of Montana, North and South Dakota, in South Africa, Iran, Afghanistan, Thailand and India. In this process, water infiltrates in the upper slope to a relatively impermeable layer, moves laterally downslope carrying dissolved salts and discharges at a lower point or depression. The water evaporates there leaving the salts behind. The development of saline seeps then involves two areas in the field—the recharge and the discharge areas (Fig. 10.4).

Sodicity

Sodicity is a phyco-chemical state of soil caused by the presence of high proportion (>15 percent) of exchangeable sodium ions on the surfaces of soil colloids so that they become highly dispersive and sticky and at the same time highly alkaline (pH usually 8.2 and above). Sodicity also makes the soil impermeable under wet

condition, causes slacking of aggregates and can create surface crusts when dried. The predominance of Na^+ ions in soil solution and in exchange positions can occur under certain conditions in semi-arid and arid regions, such as in some salt lakes and coastal areas. Usually, Ca^{2+} and Mg^{2+} are dominant cations in arid and semi-arid soils. When these ions are precipitated from solution as calcium and magnesium compounds, the predominance of Na^+ ions in soil solution and exchange sites and causes sodicity. Van Breemen and Burman (2002) suggested some mechanisms of sodification of soil including (i) prolonged leaching, natural or as desalinization effort, removes salts and Ca^{2+} ions from soil solution resulting in the prevalence of Na^+ ions, (ii) relatively greater accumulation of Na-salts that cause higher proportion of soluble and exchangeable Na^+, (iii) accumulated Na_2SO_4 in some lake beds become reduced in wet conditions and in the presence of organic matter to Na_2CO_3 that causes sodicity, and (iv) presence of HCO_3^- ions in excess of $Ca^{2+} + Mg^{2+}$ ions in soil solutions; if Ca^{2+} are considerably lower than HCO_3^- ions, all the Ca^{2+} ions are precipitated as $CaCO_3$, and Na^+ ions predominate in soil solution and in colloidal surfaces causing soil sodicity.

10.3 Distribution of Saline Soils

Although an earlier estimate shows that there were 932.2 million hectares of salt affected soils, including 351.5 M ha saline and 581.0 M ha sodic soils according FAO report of 2000, the total global area of salt-affected soils including saline and sodic soils was 831 million hectares (Martinez-Beltran and Manzur 2005), extending over all the continents including Africa, Asia, Australasia, and the Americas. Based on the FAO/UNESCO Soil Map of the world, the total area of saline soils is 397 million ha and that of sodic soils is 434 million ha. Most of the salt affected land lies in the arid and semiarid environment. Figs. 10.5 and 10.6 show the global distributions of saline and sodic soils.

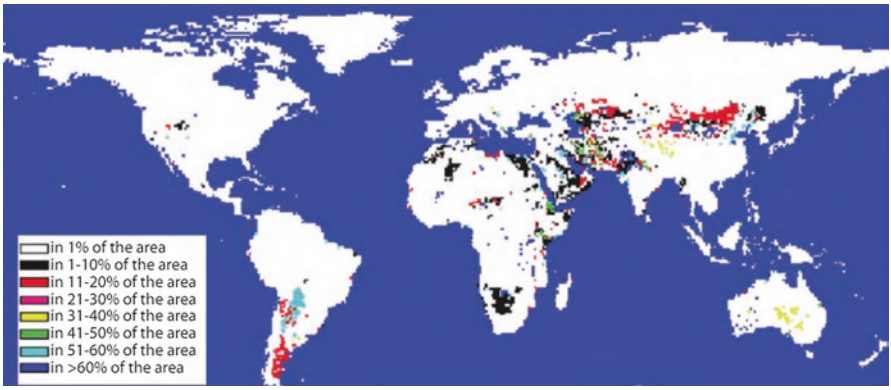
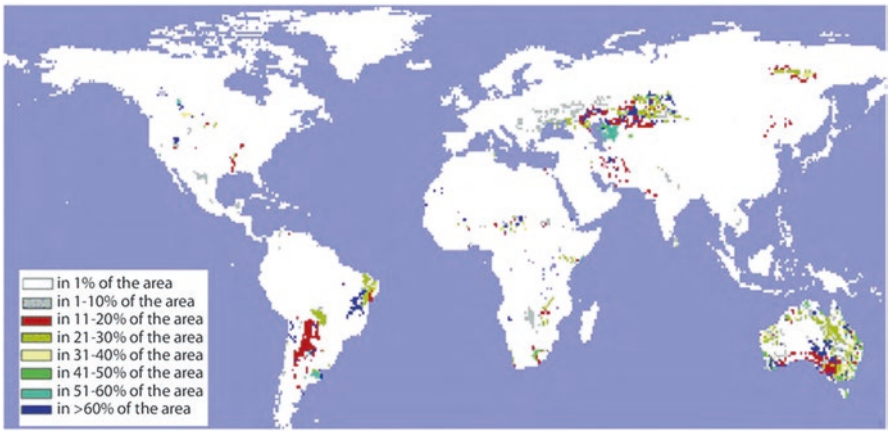

in 1% of the area
in 1-10% of the area
in 11-20% of the area
in 21-30% of the area
in 31-40% of the area
in 41-50% of the area
in 51-60% of the area
in >60% of the area

Fig. 10.5 Global distribution of saline soils. (Source FAO/UNESCO Soil Map of the World)


in 1% of the area
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in 11-20% of the area
in 21-30% of the area
in 31-40% of the area
in 41-50% of the area
in 51-60% of the area
in >60% of the area

Fig. 10.6 Global distribution of sodic soils. (Source FAO/UNESCO Soil Map of the World)

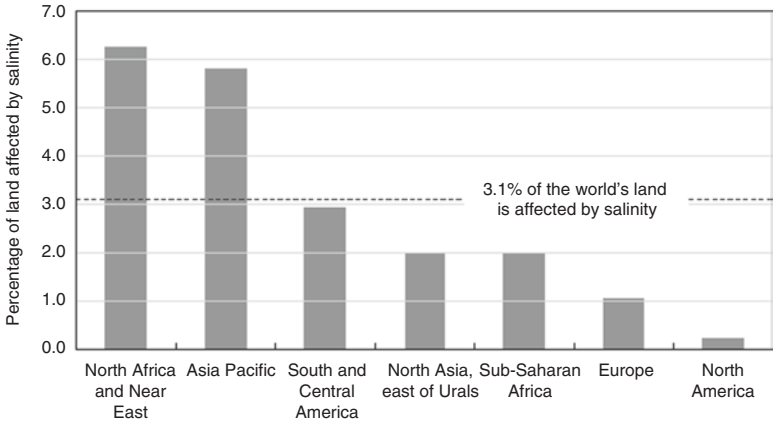

Fig. 10.7 Percentage of land area affected by salinity in different regions. (Source: FAO 2006)

The proportion of land area affected by salinity in different regions of the world is shown in Fig.10.7.

Salt affected soils occur in more than 75 countries of the world, mostly in Africa (31) and Asia (25), and some in the Americas (13). Human induced salinity has invaded over the last few decades to several major irrigation schemes throughout the world (Qadir et al. 2007), including Indo-Gangetic Basin in India (Gupta and Abrol 2000), Indus Basin in Pakistan (Aslam and Prathapar 2006), Yellow River Basin in China (Chengrui and Dregne 2001), Euphrates Basin in Syria and Iraq (Sarraf 2004), Murray-Darling Basin in Australia (Rengasamy 2006), and San Joaquin Valley in the United States (Oster and Wichelns 2003). The regional distribution of saline soils is shown in Table 10.4.

Table 10.4 Regional distribution of saline soils

Region	Area (million hectare)
Africa	69.5
Near and Middle east	53.1
Asia and Far East	19.5
Latin America	59.4
Australia	84.7
North America	16.0
Europe	20.7
Total	**322.9**

Source: FAO/UNESCO Soil Map of the World

Soil salinization is a major threat to agricultural production systems and food security in many countries. Salinity affects almost 1 billion hectare of land worldwide that is equivalent to 7% of earth's continental extent (Metternicht and Zinck 2003; Yensen 2008). Patel et al. (2011) reported that about 7 million hectares of land in India alone have saline soils. Shrivastava and Kumar (2015) noted that not only has high soil salinity affected an estimated area of 20% of total cultivated lands and 33% of global irrigated agricultural lands, but the salinized areas are increasing at an annual rate of 10 percent for various reasons including low precipitation, high evaporation, using saline water for irrigation and poor drainage. Jamil et al. (2011) reported that >50% of global arable land would be affected by soil salinity by 2050.

10.4 Field Indicators of Soil Salinity

There are some symptoms that can suggest whether salinity might be affecting a site. Some of these indicators are listed below. Readers should be aware that these indicators are not always easy to detect. One or more symptoms may develop or no symptom may be apparent at the initial stage of salinization. Moreover, symptoms usually develop in soils or plants at an advanced stage of salinity when remedial measures can be time consuming and costly. It is wiser to prevent salinity than to cure it.

- Patches of leaf-burn in the crop field.
- Patches of salt-tolerant plants developing.
- Increased soil wetness in semiarid and arid areas.
- Irregular patterns of crop growth and lack of plant vigor.
- Areas becoming bare and 'scalded'.
- White spots and streaks in the soil
- White crusting on the surface.

10.5 Effect of Soil Salinity on Plants

Soil salinity exerts its adverse effects on glycophytic plants (any plant that will only grow healthily in soils with a low content of salts) in two different ways:

(a) By reducing total soil water potential through osmotic effects of salts, and
(b) By the activity of specific ions.

The relative contribution of the two mechanisms is not always predictable because of wide variation among soils, salts and plants (Yadav et al. 2011). The initial effect of salinity, especially at low to moderate concentrations, is due to its osmotic effects. Plants cannot absorb enough water from soil if the soil water potential is very low due to the presence of high concentrations of salts in soil solution. In a way, salt stress resembles water stress. However, some plants can adapt to some degree of salinity through osmotic adjustments, so that they can maintain a potential for the influx of water (Ghoulam et al. 2002). They are salt tolerant plants.

Soil salinity has been a major concern to global agriculture throughout human history (Lobell et al. 2007). In the recent years, more saline areas are being brought under cultivation for producing food, wood, biofuel, etc. (Haque 2006). Some crops are very sensitive to even low level of soil salinity, while some others are relatively tolerant. For example, cotton, an important cash crop worldwide, is classified as one of the most salt-tolerant crops and considered a pioneer crop in reclamation of saline soils. But its growth, yield and fiber quality are negatively affected by excessive salts in the soil (Higbie et al. 2010). In general, soil salinity delays and reduces germination and emergence, decreases cotton shoot growth, and may finally lead to reduced seed cotton yield and fiber quality at moderate to high salinity levels (Khorsandi and Anagholi 2009).

Effects of salinity on the growth of crop plants have considerably been investigated worldwide (Essa 2002; FAO 2002; Munns 2005; Maghsoudi and Maghsoudi 2008; Ashraf 2009; Chaum et al. 2011; Nasser and Sholi 2012; Dong 2012; Zeinolabedin 2012; Moradi and Zavareh 2013). It is often suggested that most of the salt stresses in plant are due to the abundance of NaCl and Na_2SO_4 in soil (Amiri et al. 2010). However, there are multiple types of salts in saline soils and the composition of salts also varies greatly among locations (Tobe et al. 2002). Each salt may have a different effect on the growth of plants (Tobe et al. 2003).

Salinity greatly reduces seed germination, seedling growth and crop establishment (Azizi et al. 2011; Naseri et al. 2012; Ewase et al. 2013; Salehifar et al. 2010; Sadeghi 2010), although the effect in early vegetative growth stage is more pronounced (Botia et al. 2005; Wilson et al. 2000; del Amor et al. 2001). Reduction in length and weight of root and shoot at early growth stages in response to salinity has been reported for several crop plants (Garg and Singla 2004; Parida and Das 2005). Salinity reduces leaf number, leaf area and photosynthesis (Sadeghi 2010; Ashraf 2001; Romero-Aranda et al. 2001). High salinity reduces nodulation of legumes (Mudgal et al. 2009; Mudgal et al. 2010). Several investigators have observed adverse effects of salinity on metabolic processes related to the growth of glyco-

phytic plants (Dhanapackiam and Ilyas 2010). Salinity seriously affects leaf chlorophyll content, photosynthetic carbon metabolism and photosynthetic efficiency. Salinity drastically affects nitrogen metabolism (Mansour 2000; Santos et al. 2002) and carbon metabolism (Balibrea et al. 2003).

Specific ion effect includes ion toxicity and/or nutritional disorders caused by one or some of the ions commonly associated with salinity including the cations Na^+, Ca^{2+} and Mg^{2+}, and the anions Cl^-, SO_4^{2-} and HCO_3^-. Both Na^+ and Cl^- are toxic to plants. High concentration of NaCl acts antagonistically to the uptake of the other nutrients, such as K^+, Ca^{2+}, N and P. Increased concentration of NaCl in soil solution increases concentrations of Na^+ and Cl^- and reduces concentrations of Ca^{2+}, K^+ and Mg^{2+} in tissues of many plant species (Bayuelo-Jimenez et al. 2003). Accumulation of Na^+ in leaf tissues results in necrosis and abscission of leaves (Parvaiz and Satyawati 2008). Excess Na^+ and Cl^- interfere with the uptake of P, Fe and Zn. The high levels of Na^+ or Na^+:K^+ ratio can also disrupt various enzymatic processes in the cytoplasm, and the disruption in protein synthesis appears to be an important cause of damage by Na^+ (Tester and Davenport 2003). Radi et al. (2013) observed inhibition of several physiological and biochemical processes of plants due to salinity. However, the Ca^{2+} significantly affects the salinity responses of plants, particularly during the initial growth (Tobe et al. 2002, 2003).

An increase in the concentration of certain dissolved ions in soil may enhance their uptake, increase their concentrations in plant tissue and become phytotoxic above a level. This level depends on the type of plants, type of plant tissues and conditions of soils. However, ions that may create phytotoxicity in saline soil generally include Cl^-, B (as H_3BO_3 and $H_2BO_3^-$) and Al^{2+}. Specific ionic stresses may disrupt integrity and selectivity of root plasma membrane, homeostasis of essential ions and numerous metabolic activities (Zhu 2001). Many saline soils used for cereal production have low levels of plant-available Zn because Zn may be complexed with or compete with dissolved salts (CO_3^{2-}, SO_4^{2-}, Na^+) at alkaline pHs. Since crops are the principal route of most essential minerals into the human body, salinity may indirectly contribute to mineral deficiency in billions of people. The primary salinity effects give rise to numerous secondary ones such as oxidative stress, characterized by accumulation of reactive oxygen species (H_2O_2, O^{2-}, OH), potentially harmful to biomembranes, proteins, nucleic acids and enzymes (Gomez et al. 2004). Antioxidative enzymes such as superoxide dismutase, catalases, peroxidises, etc. enhance detoxication of reactive oxygen species. The relatively salt-tolerant species (e.g. pea genotypes) have increased activities of certain antioxidative enzymes (Hernandez et al. 2001).

Both Na^+ (a beneficial element) and Cl^- (a micronutrient) are potentially toxic in excessive concentrations, triggering specific disorders and causing substantial damages to crops. Under excessive Na^+ and Cl^- in rhizosphere concentration, there are competitive interactions with other nutrient ions such as K^+, NO_3^-, $H_2PO_4^-$ for binding sites and transport proteins in root cells, and latter for retranslocation, deposition and partitioning within the plant (Tester and Davenport 2003). Significantly enhanced uptake and accumulation of Na and Cl accompanied with a decrease in K concentration in the same tissues was obtained under moderate NaCl salinity

(Ondrasek et al. 2009). The high K/Na and Ca/Na ratios are essential for normal plant functioning (Chinnusamy et al. 2005); but Ondrasek et al. (2009) observed 13-fold decline in Ca/Na under salinity in radish, 113-fold in strawberry and 150-fold in muskmelon leaf tissues.

As a result of all these responses to salinity, uneven and stunted crop stands develop and crop yield is greatly reduced. According to USDA-NRCS (2011), 50 percent yield of the following fruit crops are reduced at EC_e range of 2.5–4.9 dS m^{-1}: grapefruit *(Citrus paradisi)*, orange *(Citrus sinensis)*, peach *(Prunus persica)*, apricot *(Prunus armeniaca)*, almond *(Prunus dulcis)*, plum *(Prunus domestica)*, blackberry *(Rubus sp.)*, boysenberry *(Rubus ursinus)* and strawberry *(Fragaria sp.)*. Yields of potato *(Solanum tuberosum)*, maize *(Zea mays)*, sweet potato *(Ipomoea batatas)*, pepper *(Capsicum annuum)*, lettuce *(Lactuca sativa)*, radish *(Raphanus sativus)*, onion *(Allium cepa)*, carrot *(Daucus carota)*, flax *(Linum usitatissimum)*, broad bean *(Vicia faba)*, bean *(Phaseolus vulgaris)* and turnip *(Brassica rapa)* are reduced by 50% at EC_e values between 3.6 and 5.9 dS m^{-1}.

10.6 Effects of Sodicity on Plant Growth

Sodic soils adversely affect plant growth in one or more of the following ways:

Poor physical conditions give poor tilth and adverse soil moisture-aeration relationships. Excess exchangeable sodium deteriorates the physical properties of soils. Clay particles remain dispersed (Bauder and Brock 2001), so that stable aggregates cannot develop there. For such physical conditions, sodic soils have low permeability to air and water. Dense, impermeable surface crusts may form as a result of dispersion (Falstad 2000). A compact layer of clay develops in the subsoil of some sodic soils due to migration of dispersed clay particles. This layer restricts the development of root system of plants. As a result, the growth of plants is reduced (Qadir et al. 2007; Garg and Malhotra 2008).

Secondly, sodic soils have low availability of some nutrient elements. Excess exchangeable sodium elevates the pH of soils above 8.2. Although soil pH has little direct effect on plants, the extremely alkaline pH of sodic soils lowers the availability of some essential plant nutrients, such as P, Fe, Mn and Zn, with concomitant decrease in their availability to plants. At very high soil pH of sodic soils, the concentration of the elements calcium and magnesium in the soil solution is reduced due to the formation of relatively insoluble calcium and magnesium carbonates by reaction with soluble carbonate of sodium, etc. and results in their deficiency for plant growth.

Thirdly, the accumulation of certain elements in plants at toxic levels may result in plant injury or reduced growth and even death (specific ion effects). Elements more commonly toxic in sodic soils include sodium, molybdenum and boron. Typical sodium toxicity symptoms are leaf burn, scorch and dead tissue along the

outside edges of leaves. Sodium toxicity is often modified or reduced if sufficient calcium is available in the soil. For at least a few annual crops, excess sodium in soil may produce calcium deficiency.

A list of plants suffering from toxicities of sodium and boron in sodic soils is given below:

Sodium toxicity Avocado (*Persea Americana*), grapefruit (*Citrus paradisi*), orange (*Citrus sinensis*), peach (*Prunus persica*), beangreen (*Phaseolus vulgaris*), cotton (*Gossypium hirsutum*), maize (*Zea mays*), peas (*Pisum sativum*), mung (*Phaseolus aurus*), mash (*Phaseolus mungo*), lentil (*Lens culinaris*), groundnut (*Arachis hypogaea*), gram (*Cicer arietinum*) and cowpea (*Vigna sinensis*).

Boron toxicity Lemon (*Citrus limon*), blackberry (*Rubus spp.*), avocado (*Persea Americana*), grapefruit (*Citrus paradisi*), orange (*Citrus sinensis*), apricot (*Prunus armeniaca*), peach (*Prunus persica*), cherry (*Prunus avium*), plum (*Prunus domestica*), grape (*Vitis vinifera*), walnut (*Juglans regia*), pecan (*Carya illinoiensis*), cowpea (*Vigna unguiculata*), onion (*Allium cepa*), garlic (*Allium sativum*), sweet potato (*Ipomoea batatas*), wheat (*Triticum eastivum*), barley (*Hordeum vulgare*), sunflower (*Helianthus annuus*), mungbean (*Vigna radiate*), sesame (*Sesamum indicum*), lupine (*Lupinus hartwegii*), strawberry (*Fragaria spp.*), kidney bean (*Phaseolus vulgaris*), lima bean (*Phaseolus lunatus*) and groundnut (*Arachis hypogaea*).

10.7 Reclamation and Management of Saline Soils

Integrated soil, water and crop management practices are needed to manage saline soils for crop production. Many low salinity soils can be profitably used for suitable salt tolerant crops without undertaking time consuming and costly reclamation procedures. In some cases, salts may either be diluted to a tolerable limit or removed by leaching. Some soils are more profitably used for salt farming. Where there is a salt crust on the surface, decrusting may be done by mechanical scraping and with soil flushing for improving crop growth. Leaching is needed in the reclamation of most saline soils. It refers to the removal of excess salts from the soil profile with the percolating water. Leaching requires more water than normal irrigation, and the amount of extra water needed must be apprehended before leaching is done. Some soils may need decrusting before leaching. Some soils are only slightly saline; for shallow-rooted crops the salts may be driven below the root zone by temporary leaching. This technique will need less water than normal leaching. No chemical amendment is normally needed for reclamation of soils which contain excess salts only without excess exchangeable sodium.

10.7.1 Principles of the Management of Saline Soils

Management practices for saline soils may be based on the following principles:

- Selection of salt tolerant crops: A set of crops having threshold values close to the ECe of the soil under consideration should be selected for different crop seasons. It can be a viable option for sustainable management of soils with low salinity without employing significant reclamation efforts. There are some crops that can tolerate moderate to high salinity.
- Dilution of salts in the root zone: Salts affect crops via the roots (unless sprinkler irrigation is done). Salt hazard can be reduced if salt concentration in the root zone can be lowered (drip irrigation with good quality water is an efficient system of diluting salts around the roots).
- Improving soil structure with organic amendments to improve infiltration and hydraulic conductivity. Decompaction and destruction of root restrictive layers improve rooting of crop plants and hydrological conditions of the soil.
- Improving leaching of salts by irrigation and drainage. Extra water is needed to leach excess salts out of the root zone. The quality of irrigation water and draining away the salty water safely should also be important considerations.
- Reducing evaporation with mulch or cover crops. Higher evaporation concentrates soil solution and increases capillary rise of groundwater.
- Maintaining the groundwater table at a safe depth below the root zone.
- Maintaining a crop while reclamation is underway. The crop will be benefitted from the management practices and compensate for the cost of reclamation.

10.7.2 Selection of Salt Tolerant Crops

Several management practices can reduce salt levels in the soil, but it is sometimes either impossible or too costly to reduce soil salinity to the desired levels. In some cases, the only viable management option is to grow salt-tolerant crops. Salt tolerant crops are also helpful and profitable during reclamation of saline soils. Generally, tolerance of a crop to soil salinity is based on the following three criteria:

(i) The ability of the crop to survive on saline soils,
(ii) The yield of the crop on saline soils, and
(iii) Relative yield of the crop on a saline soil as compared to its yield on a nonsaline soil under similar growing conditions.

Salt tolerance on the basis of simple ability of a crop plant to survive is of limited practical significance in irrigation agriculture. Yield on saline soils is of greater agronomic importance, but the third criterion provides a better basis of comparison among diverse crops. In FAO Irrigation and Drainage Paper 29, Ayers and Westcot (1985) discussed irrigation water quality parameters related to soil salinity. They

Table 10.5 EC_e values for yield reduction potentials of different field crops

Field Crops	Yield reduction potential at EC_e, dS m^{-1}				
	10%	20%	30%	50%	100%
Barley *(Hordeum vulgare)*	8.0	10	13	18	28
Cotton *(Gossypium hirsutum)*	7.7	9.6	13	17	27
Sugarbeet *(Beta vulgaris)*	7.0	8.7	11	15	24
Sorghum *(Sorghum bicolor)*	6.8	7.4	8.4	9.9	13
Wheat *(Triticum aestivum)*	6.0	7.4	9.5	13	20
Wheat, durum *(Triticum turgidum)*	5.7	7.6	10	15	24
Soybean *(Glycine max)*	5.0	5.5	6.3	7.5	10
Cowpea *(Vigna unguiculata)*	4.9	5.7	7.0	9.1	13
Peanut *(Arachis hypogaea)*	3.2	3.5	4.1	4.9	6.6
Rice (paddy) *(Oriza sativa)*	3.0	3.8	5.1	7.2	11
Sugarcane *(Saccharum officinarum)*	1.7	3.4	5.9	10	19
Corn (maize) *(Zea mays)*	1.7	2.5	3.8	5.9	10
Flax *(Linum usitatissimum)*	1.7	2.5	3.8	5.9	10
Broadbean *(Vicia faba)*	1.5	2.6	4.2	6.8	12
Bean *(Phaseolus vulgaris)*	1.0	1.5	2.3	3.6	6.3

listed common field crops, vegetable crops and fruit crops and their yield reduction potentials at different soil salinity (EC_e) and water salinity (EC_w) levels. Based on their data Tables 10.5, 10.6, and 10.7 were constructed to show the relative tolerances of soil salinity of different field crops, vegetable crops, and fruit crops respectively. Absolute salinity tolerance, however, depends on soil types, crop growth stages, climate and cultural practices. These data can be used as guidelines for the selection of crops for soils of different salinity levels.

The maximum average EC_e value the crop can tolerate without any decline in yield is known as the threshold value. The percent loss in yield for each unit increase in EC_e above the threshold is known as slope coefficient.

The following lists of salt sensitive and salt tolerant crops can be prepared from different unpublished web sources:

Sensitive crops (threshold ECe values in parentheses) bean (1.0), carrot (1.0), strawberry (1.0), onion (1.2), almond (1.5), blackberry (1.5), plum (1.5), apricot (1.5), orange (1.7), peach (1.7), ground nut (1.8), etc.

Moderately tolerant to tolerant crops (threshold ECe values in parentheses) Red beet (4.0), harding grass (4.6), squash (4.7), cowpea (4.9), soybean (5.0), birdsfoot trefoil (5.0), perennial rye grass (5.6), durum wheat (5.7), barley forage (6.0), wheat (6.0), sorghum (6.8), sugar beet (7.0), cotton (7.7), barley (8.0), etc.

Cl^- tolerant crops Perennial ryegrass, durum wheat, barley (forage), wheat, sorghum Bermuda grass, sugar beet, wheat grass, crested fairway, cotton, tall wheat grass, barley, etc.

Table 10.6 EC_e values for yield reduction potentials of different vegetable crops

Vegetable Crops.	Yield reduction potential at EC_e, dS m^{-1}				
	10%	20%	30%	50%	100%
Beet, red *(Beta vulgaris)*	4.0	5.1	6.8	9.6	15
Squash, scallop *(Cucurbita pepo)*	3.2	3.8	4.8	6.3	9.4
Broccoli *(Brassica oleracea botrytis)*	2.8	3.9	5.5	8.2	14
Tomato *(Lycopersicon esculentum)*	2.5	3.5	5.0	7.6	13
Cucumber *(Cucumis sativus)*	2.5	3.3	4.4	6.3	10
Spinach *(Spinacia oleracea)*	2.0	3.3	5.3	8.6	15
Celery *(Apium graveolens)*	1.8	3.4	5.8	9.9	18
Cabbage *(Brassica oleracea capitata)*	1.8	2.8	4.4	7.0	12
Potato *(Solanum tuberosum)*	1.7	2.5	3.8	5.9	10
Corn, sweet (maize) *(Zea mays)*	1.7	2.5	3.8	5.9	10
Sweet potato *(Ipomoea batatas)*	1.5	2.4	3.8	6.0	11
Pepper *(Capsicum annuum)*	1.5	2.2	3.3	5.1	8.6
Lettuce *(Lactuca sativa)*	1.3	2.1	3.2	5.1	9.0
Radish *(Raphanus sativus)*	1.2	2.0	3.1	5.0	8.9
Onion *(Allium cepa)*	1.2	1.8	2.8	4.3	7.4
Carrot *(Daucus carota)*	1.0	1.7	2.8	4.6	8.1
Bean *(Phaseolus vulgaris)*	1.0	1.5	2.3	3.6	6.3
Turnip *(Brassica rapa)*	0.9	2.0	3.7	6.5	12

Table 10.7 ECe values for yield reduction potentials of different fruit crops

Fruit Crops	Yield reduction potential at EC_e, dS m^{-1}				
	10%	20%	30%	50%	100%
Date palm *(phoenix dactylifera)*	4.0	6.8	11	18	32
Grapefruit *(Citrus paradisi)*	1.8	2.4	3.4	4.9	8.0
Orange *(Citrus sinensis)*	1.7	2.3	3.3	4.8	8.0
Peach *(Prunus persica)*	1.7	2.2	2.9	4.1	6.5
Apricot *(Prunus armeniaca)*	1.6	2.0	2.6	3.7	5.8
Grape *(Vitus sp.)*	1.5	2.5	4.1	6.7	12
Almond *(Prunus dulcis)*	1.5	2.0	2.8	4.1	6.8
Plum, prune *(Prunus domestica)*	1.5	2.1	2.9	4.3	7.1
Blackberry *(Rubus sp.)*	1.5	2.0	2.6	3.8	6.0
Boysenberry *(Rubus ursinus)*	1.5	2.0	2.6	3.8	6.0
Strawberry *(Fragaria sp.)*	1.0	1.3	1.8	2.5	4

The following list of trees and shrubs was prepared from data of the College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University (Anon 2015):

Trees tolerant to saline soils Black walnut (*Juglans nigra*), Eastern red cedar (*Juniperus virginiana*), Golden raintree (*Koelreuteria paniculata*), Southern magnolia (*Magnolia grandiflora*), Sweetbay magnolia (*Magnolia virginiana*), Carolina

cherrylaurel (*Prunus caroliniana*), Japanese black pine (*Pinus thunbergiana*), White poplar (*Populus alba*), Red oak *Quercus rubra*), Live oak (*Quercus virginiana*), Bur oak (*Quercus macrocarpa)*, Black locust (*Robinia pseudoacacia*), Japanese tree lilac (*Syringa reticulate*), Bald cypress (*Taxodium distichum*),Chaste tree (*Vitex anguscastus*), White oak (*Quercus alba*), and Pin oak (*Quercus palustris*).

Trees tolerant to salt spray Common larch (*Larix deciduas*), Sweetgum (*Liquidambar styraciflua*), Black gum (*Nyssa sylvatica*), Colorado spruce (*Picea pungens*), Austrian pine (*Pinus nigra*), Longleaf pine (*Pinus palustris*), Japanese black pine (*Pinus thunbergiana*), White poplar (*Populus alba*), Black cherry (*Prunus serotina*), Bur oak (*Quercus macrocarpa)*,Willow oak (*Quercus phellos*), English oak (*Quercus robur*),Black locust (*Robinia pseudoacacia*), Weeping willow (*Salix alba*),Corkscrew willow (*Salix matsudana*), Japanese pagodatree (*Sophora japonica*), and Japanese tree lilac (*Syringa reticulate*).

Shrubs tolerant to saline soils or salt spray Red chokeberry (*Aronia arbutifolia*), Saltbush (*Baccharis halmifolia*), Littleleaf boxwood (*Buxus microphylla*), Beautyberry (*Callicarpa americana*), False cypress (*Chamaecyparis pisifera*), Summersweet (*Clethra alnifolia*), Red osier dogwood (*Cornus sericea*), Spreading cotoneaster (*Cotoneaster divaricatus*), Rockspray cotoneaster (*Cotoneaster horizontalis*), Scotch broom (*Cytisus scoparius*), Gardenia (*Gardenia jasminoides*), Rose-of-Sharon (*Hibiscus syriacus*), House hydrangea (*Hydrangea macrophylla*), St. John's wort (*Hypericum calycinum*), Chinese holly (*Ilex cornuta*), Japanese holly (*Ilex crenata*), Inkberry (*Ilex glabra*), Yaupon holly (*Ilex vomitoria*), Anise (*Illicium floridanum*), Chinese juniper (*Juniperus chinensis*), Common juniper (*Juniperus communis*), Shore juniper (*Juniperus conferta*), Creeping juniper (*Juniperus horizontalis*), Amur privet (*Ligustrum amurense*), Tatarian honeysuckle (*Lonicera tatarica*), Wax myrtle (*Myrica cerifera*), Bayberry (*Myrica pennsylvanica*), Mock orange (*Philadelphus coronaries*), Mugo pine (*Pinus mugo*), Shrubby cinquefoil (*Potentilla fruticosa*), Purple-leaf sand cherry (*Prunus x cistena*), Cherry laurel (*Prunus laurocerasus*), Beach plum (*Prunus maritime*),Pyracantha (*Pyracantha coccinea*),Indian hawthorn (*Rhapiolepis indica*),Staghorn sumac (*Rhus typhina*), Lady Banks rose (*Rosa banksiae*), Rugosa rose (*Rosa rugosa*), Scotch rose (*Rosa spinosissima*), Elderberry (*Sambucus Canadensis*), Japanese spirea (*Spiraea japonica*), Bumalda Japanese spirea (*Spiraea x bumalda*), Snowberry (*Symphoricarpos albus*), Lilac (*Syringa vulgaris*), Tamarisk (*Tamarix ramosissima*), English yew (*Taxus baccata*), Japanese yew (*Taxus cuspidate*), Highbush blueberry (*Vaccinum corymbosum*), Arrowwood (*Viburnum dentatum*), and European cranberry bush (*Viburnum opulus*).

10.7.3 Salt Scraping

Scraping is the simplest way of reclaiming a saline soil on a small scale (Fig. 10.8). In soils of arid and semiarid regions where a salt crust often develops on the soil

Fig. 10.8 Salt scraping. (Image source: Rutger2 at nl.wikipedia)

surface due to high evaporation and low leaching (Kara and Willardson 2006), this method of mechanical removal of salts is employed. In such environmental conditions, this practice is appropriate as suggested by Kang et al. (2013).

Removal of the salt layer exposes the relatively low salinity subsoil which gives a better yield. But, this process has a limited success because salts tend to accumulate again. Salts further accumulate due to lowering the ground level through salt scraping or soil desurfacing in relation to the water table. In other words, this method intensifies the problem over time. Scraping of salts improves plant growth only temporarily. Moreover, disposal of scraped salts is a problem. Scraping also involves high labor cost.

10.7.4 Salt Flushing

Salts in surface crusts in soils with low permeability are sometimes washed away by flushing with water over the surface. For flushing, the field is first ponded with water to dissolve the salts. Soil flushing is particularly feasible where flushed salts can be disposed of with irrigation or rainwater in nearby natural drainage systems such as rivers. A sufficient downward gradient is required to carry the water away. Therefore, this method is not practical in landlocked fields. Otherwise, it may pollute surrounding areas. Salt flushing is most effective initially; the efficiency decreases as salt concentrations diminish. In this method only the surface area is being somewhat remedied, the rest of the soil profile is still contaminated. This method is also of limited practical significance because the amount of salts that can be flushed away from a soil is rather small and salts keep accumulating on the surface again. Fig. 10.9 shows a field being flushed for salinity reclamation.

Fig. 10.9 A layer of salt on soil surface is being flushed. (Image courtesy of USDA.NRCS)

10.7.5 Leaching

Removal of excess salts below the root zone and through the soil profile with percolating water is known as leaching. Leaching is a natural process in well drained soils of the humid regions. In arid and semiarid regions, there is not enough rain water to leach the salts released by weathering or accumulated by capillary rise of groundwater. There leaching is aided by irrigation if enough water is available. Soil permeability is usually low and the groundwater table is very high in saline soils of the humid regions. So, artificial drainage is needed to remove excess water and salts and to lower the groundwater table. However, in areas of good natural drainage, there is no need of artificial drainage for leaching the salts. There the problem is the capillary rise of salty groundwater to the soil surface due to low precipitation and high evaporation. Leaching of salts in permeable soils is best performed by an integration of irrigation and drainage. In impermeable soils, leaching might be efficient if the permeability could be improved by organic amendments prior to the leaching effort. Moreover, several other factors are involved in the success of the leaching process. Some of these factors are: (i) electrical conductivity (ECe) of the soil, (ii) number of units of ECe to be lowered, (iii) amount of water used, (iv) salinity level of irrigation water (ECw), (v) irrigation system (vi) soil texture (vii) salt tolerance of the crop (viii) depth of roots, etc.

However, leaching is by far the most effective method of the reclamation of saline soil. Leaching should preferably be done when the soil moisture content is low and the groundwater table is deep.

Border flooding is a method of irrigation in which the field is surrounded by an earthen border to restrict the water within it. Border flooding irrigation can be used

for leaching of salts from saline soils with either continuous ponding or intermittent ponding. Before flooding, the land is leveled to spread the water evenly over the field plowed to facilitate infiltration and percolation. When the continuous ponding method is used, the field is deeply flooded with a single application of water and the water is allowed to percolate. In intermittent ponding method several applications of water at suitable intervals are given in small amounts at any one time. Continuous ponding method is usually used in soils with better permeability so that percolation and leaching processes are faster. Generally, the amount of water required for such a leaching method is about one centimeter for reclaiming each centimeter of the soil profile. However, the amount of water needed for leaching may depend on soil texture. The intermittent ponding method is used in areas of low water availability. The amount of water for leaching also depends on the salinity level of the irrigation water (as discussed in the context of leaching requirement, LR). As water with a low salt-content is not always available, studies have revealed that saline groundwater can also be used for leaching, provided that the amount of water needed would be higher. There are some practices including subsoiling, subsoiling with inversion, auger hole piercing, etc. for improving permeability and breaking impermeable and compacted layers. There may be some cases where less permeable layers overlie highly permeable subsoils. Augur piercing by making about 10 cm diameter holes up to a depth of 2.5 m and then filling the holes with sand may improve rate of leaching. Use of some amendments (sand, gypsum, manures) can also be used to enhance leaching in impermeable soils.

The following factors determine the amount of water needed for salt reclamation through leaching – salt content of the soil, salinity level to achieve, depth to which reclamation is desired, type of crops grown and soil characteristics. A useful rule of thumb is that a unit depth of water will remove nearly 80 percent of salts from a unit soil depth. Thus 30 cm water passing through the soil will remove approximately 80 percent of the salts present in the upper 30 cm of soil. To leach soluble salts in irrigated soils, more water than required to meet the evapotranspiration needs of the crops must pass through the root zone. This additional irrigation water has typically been expressed as the leaching requirement (LR). Leaching requirement was originally defined as the fraction of infiltrated water that must pass through the root zone to keep soil salinity from exceeding a level that would significantly reduce crop yield under steady conditions with associated good management and uniformity of leaching.

$$LR = \frac{EC_{iw}}{EC_{dw}},$$

Where LR is the leaching requirement, EC_{iw} is electrical conductivity of irrigation water, and EC_{dw} is electrical conductivity of drainage water. Alternatively, leaching requirement can be obtained from the following equation.

$$\frac{C_s}{C_i} = \frac{\ln(\mathrm{LR})}{\mathrm{LR} - 1},$$

where C_s is the concentration of salts in soil and C_i concentration of salts in irrigation water. This equation is independent of the pattern of plant water use, it is of general application and the authors concluded that the equation provided a better method of estimating the leaching requirements. Ayers and Westcot (1985) also presented the following equation as a guideline for calculating LR based on irrigation water salinity and crop salt tolerance.

$$LR = \frac{EC_w}{5EC_e - EC_w}$$, where EC_w is the electrical conductivity of irrigation water. The amount of water required may be calculated from the following equation:

$$\text{Amount of water to be applied} = \frac{\text{Consumptive use}}{1 - LR}$$

Consumptive use includes the amount of water transpired during plant growth plus what is evaporated from the soil surface and foliage in the crop area. It should be noted that the uniformity of water distribution over the field and the field application efficiency have not been considered in the above calculation. Several other leaching requirement models have been proposed by Corwin et al. (2007). An example of calculating the amount of water needed for leaching is given in Box 10.1.

BOX 10.1 Calculation of Leaching Requirement

Suppose, you are going to leach salts from a soil where alfalfa will be grown. The threshold ECe for alfalfa is 2.0 dS m^{-1} (salinity level for 100% yield or no yield loss) and the leaching water has an ECw of 3.1 dS m^{-1}. What is the leaching requirement? If the consumptive use of water for alfalfa in that location is 120 cm per hectare, then calculate the amount of water to be applied to meet crop needs and to leach salts.

Solution:

$$LR = \frac{3.1}{5 \times 2.0 - 3.1} = 0.45$$

Expressed in percent, it means that 45% of the irrigation water must pass through the root zone to provide sufficient leaching.

$$\text{The amount of water needed} = \frac{120}{1 - 0.45} = 218 \text{ cm ha}^{-1}$$

Answer: The LR is 0.45 and the amount of water needed is 218 cm ha^{-1}. This amount does not include distribution, conveyance, surface runoff, or other losses.

Khoshgoftarmanesh et al. (2003) conducted an experiment with five irrigation treatments to observe their effects of saline soil reclamation in Iran. The treatments were conventional irrigation practice (L0), two excess irrigation on preplanting (L1), one excess irrigation on preplanting (L2), one excess irrigation after planting (L3), and two excess irrigation after planting (L4). Changes of soil salinity were measured at two depths of 0–25 and 25–50 cm at preplant, 3–4 days after every leaching or irrigation and after harvesting. Except for treatment L0, the final ECe values of surface soil were below the EC of irrigation water. Electrical conductivity in surface soil, after plant harvesting, decreased from 67.1 dS m^{-1} before experiment) to 7.1 dS m^{-1} by L1 treatment. Jamali et al. (2012) carried out another experiment in Sindh Agriculture University for assessing the leaching effects of salts on soil. They used the following treatments: three irrigation water amounts (7.62 cm, 10.16 cm and 12.70 cm) and three interval periods (7, 14 and 21 days). The experiment was done in a Randomized Complete Block Design with four replications. The results showed that in top soil (0–30 cm) and middle soil profiles (30–60 cm), salts have been leached more than 40 percent by consuming 45.72 cm, 60 cm and 76 cm water within 7 and 14 days intervals.

10.7.6 Irrigation

Unsaturated conditions in the field during leaching can be obtained by adopting intermittent ponding or by intermittent sprinkling at rates less than the infiltration rate of the soil. Sprinkler irrigation has been found to be more effective than flooding for leaching of salts. Because of slower wetting rate under sprinkling, the zone of complete leaching at the end of irrigation extends more deeply into the profile than under flood irrigation. Drip irrigation has some advantages over flooding and sprinkler irrigation in respect to salinity control. Drip irrigation does not cause foliar accumulation of salts during irrigation. Salts are removed from the wetted areas of the rows where root density is the highest. High frequency drip irrigation applications can maintain a relatively constant soil water content and soil salinity level over time near the drip lines. Hanson and May (2004) reported that highly profitable tomato crops were obtained in saline soils through drip irrigation. However, drip irrigation system can cause salt accumulation near the periphery of the wetted areas which may be a matter of major concern if the emitter placement does not coincide well with the plant row. Salt accumulation above buried pipelines is also a concern.

Water applied in furrow irrigation moves downward and laterally from the furrows, and upward to the ridges by capillary movement. Salts are leached downward beneath the furrows, but some salts rise to the center of the ridges with water. Water is lost through evaporation and transpiration and salts accumulate. So, salts tend to concentrate in the center of the ridges in the furrow irrigation system. If seeds are placed there, they would suffer in germination and seedling emergence. Fig. 10.10 shows the distribution of salts following furrow irrigation. Seeds or seedlings must

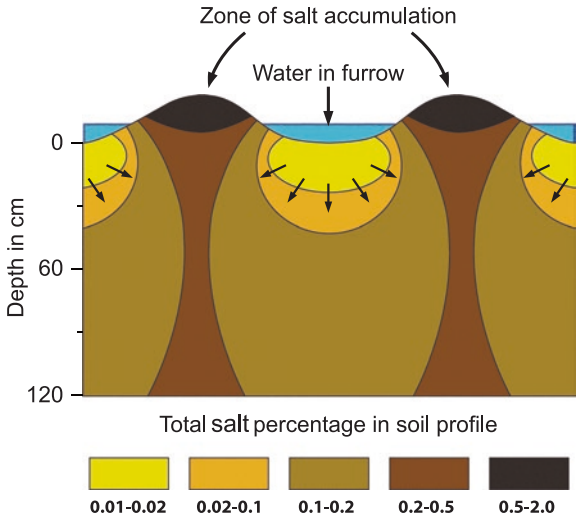

Fig. 10.10 Distribution of salts following furrow irrigation

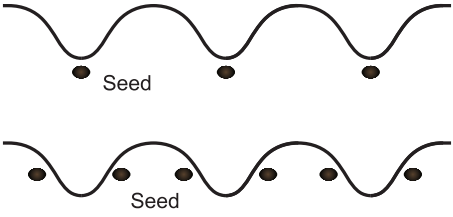

Fig. 10.11 Placement of seeds in the low saline areas. (Adapted from FAO Corporate Document Repository; Irrigation, Water Management, Chap. 3. Furrow Irrigation. www.fao.org/docrep/S8684E/s8684e04.htm)

be placed in the low saline areas (Fig. 10.11). Certain modifications of the furrow irrigation method including planting in single/double rows or on sloping beds, are helpful in getting better stands under saline conditions. With double beds, most of the salts accumulate in the center of the bed leaving the edges relatively free of salts. Sloping beds may be slightly better on highly saline soils because seeds can be planted on the slope below the zone of salt accumulation.

Double-row bed systems require uniform wetting toward the middle of the bed. This leaves the sides and shoulders of the bed relatively free from injurious levels of salinity. Alternate furrow irrigation may be desired for single-row bed systems. This is accomplished by irrigating every other furrow and leaving alternating furrows dry. Salts are pushed across the bed from the irrigated side of the furrow to the dry side (Fig. 10.12). Care is needed to ensure enough water is applied to wet all the way across the bed to prevent build up in the planted area.

Quality of irrigation water

Natural waters contain sediments and dissolved salts. These substances have an impact on the suitability of water for irrigation. Sediments in water can clog the

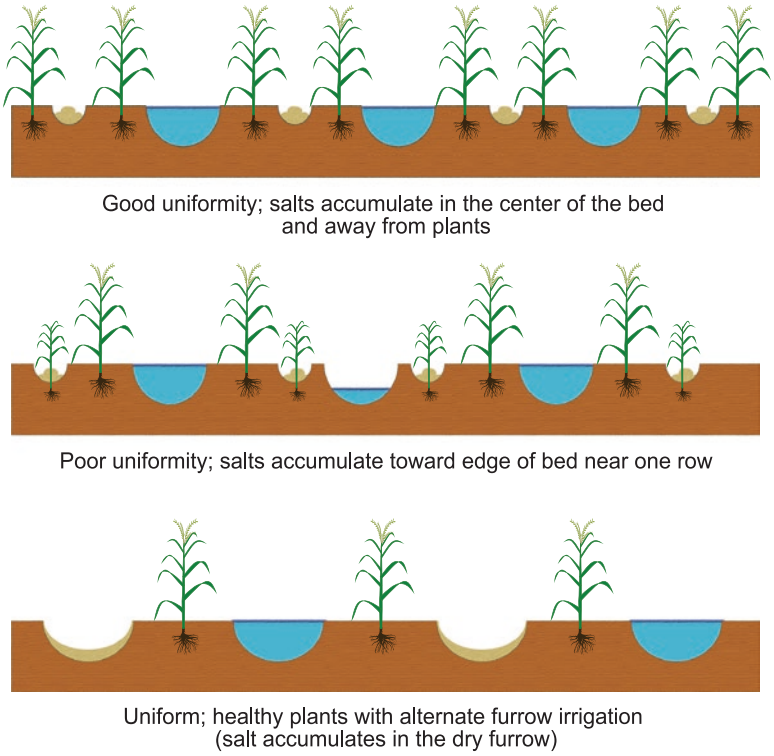
Good uniformity; salts accumulate in the center of the bed and away from plants
Poor uniformity; salts accumulate toward edge of bed near one row
Uniform; healthy plants with alternate furrow irrigation (salt accumulates in the dry furrow)

Fig. 10.12 Types of furrow irrigation for salinity control. (Adapted from Colorado State University Extension Fact Sheet; http://www.ext.colostate.edu/pubs/crops/00503.html)

nozzles of sprinklers and emitters of drip systems. Dissolved salts, on the other hand, can increase soil salinity and damage crops through toxicity. Salts in water are dissociated into cations and anions. The principal cations are Na^+, Ca^{2+}, Mg^{2+} and K^+ and the anions are Cl^-, SO_4^{2-}, NO_3^-, and HCO_3^-. Concentrations of Na^+ and Cl^- in water often exceed the critical levels. Therefore, both the salinity and the specific ion effects of irrigation water are important considerations in relation to salinity management. The salinity of water is expressed by the quantity of dissolved salts, or total dissolved solids (TDS), the unit being mg l^{-1}. This can be determined by evaporating a known amount of water to dryness in a glass or porcelain dish and measuring the mass gain. The higher the TDS, the higher is the salinity of water. Alternatively, the salinity of water can be expressed by its electrical conductivity (EC_w). Total dissolved solids can be calculated from EC_w and vice-versa according to this formula:

$$\mathrm{TDS, mg\,l^{-1}} = 640 \times \mathrm{ECw}\left(\mathrm{dS\,m^{-1}}\right)$$

It has been a matter of interesting debate and investigation whether saline ground water can be used for irrigation. The basic principle behind a sustainable agricultural system based on irrigation with saline waters in terms of long term crop yield is that the salt concentration in the root-zone has to be kept below a certain threshold level (Karlberg 2005). These levels are specific for each crop species. However, water of variable salinity <4 dS m^{-1}can be used for irrigation, but the leaching requirement and the amount of water needed for irrigation will also vary accordingly.

The electrical conductivity values range from <0.6 dS m^{-1}forfresh water to 1.5–3.0 dS m^{-1} for brackish water to about 45 dS m^{-1} for sea water. It has been observed that even slightly brackish water can affect the production of many salt-sensitive crops including bean and strawberry, and brackish water affects the moderately-sensitive crops corn, rice, potato and alfalfa. On the other hand, irrigation with brackish water may be feasible for salt tolerant crops, such as barley, sugar beet and cotton (Pitman and Lauchli 2002).

Often water of some degree of salinity or sodicity is used for irrigation. The use of such marginal-quality water would not only permit the horizontal expansion of irrigated agriculture, but would also reduce drainage disposal and associated environment problems (Oster and Grattan 2002). The use of saline-sodic water for irrigation without amendment tended to increase pH slightly after harvest of the crop. In Table 10.8, use of mixed saline and nonsaline water at various proportions for irrigation in different crops and their effects on yield is shown. It was adapted from Qadir and Oster (2004).

Reclaimed wastewater and drainage water are being used for irrigation increasingly. Table 10.9 presents the recommended limits for constituents in reclaimed water for irrigation.

Table 10.8 Proportion of saline water (%) that can be mixed with nonsaline irrigation water (ECw = 0.8 dS m^{-1}) to achieve a potential yield of 100 percent and 80 percent for selected crops

	EC_w dS m^{-1}			
	4	6	8	10
Crop	Saline water proportion (%)			
100 percent yield				
Lettuce (*Lactusa sativa*)	2	2	1	1
Alfalfa (*Medicago sativa*)	14	9	6	5
Tomato (*Lycopersicon esculentum*)	25	15	11	9
Cotton (*Gossypium hirsutum*)	100	62	44	35
80 percent yield				
Lettuce (*Lactusa sativa*)	37	23	17	13
Alfalfa (*Medicago sativa*)	80	52	39	31
Tomato (*Lycopersicon esculentum*)	78	48	35	27
Cotton (*Gossypium hirsutum*)	100	100	100	100

Table 10.9 Recommended limits for constituents in reclaimed water for irrigation

Constituent	Long-term use (mg l^{-1})	Short-term use (mg l^{-1})
Aluminum	5.0	20
Arsenic	0.10	2.0
Beryllium	0.10	0.5
Boron	0.75	2.0
Cadmium	0.01	0.05
Chromium	0.1	1.0
Cobalt	0.05	5.0
Copper	0.2	5.0
Fluoride	1.0	15.0
Iron	5.0	20.0
Lead	5.0	10.0
Lithium	2.5	2.5
Manganese	0.2	10.0
Molybdenum	0.01	0.05
Nickel	0.2	2.0
Selenium	0.02	0.02
Vanadium	0.1	1.0
Zinc	2.0	10.0

Source: EPA 2004

10.7.7 Drainage

Irrigation water brings salts of saline soils into solution, and these salts are usually leached to the ground water or can be driven away by deep surface drainage systems. Deep ditches at suitable intervals are dug and connected to a collecting ditch in surface irrigation systems. The size of the field ditches and collecting ditches depends on the volume of water to be discharged. In this system, some land becomes unavailable for cropping. An effective subsurface drainage system must be constructed to remove the salt laden groundwater, to keep the groundwater table at a safe depth below and to prevent the groundwater table to rise at or near the root zone. Various drainage systems have been described in Chap. 5 in connection with management of poorly drained soils, and all these systems can be employed to reclaim saline soils if soil conditions, such as texture, porosity, permeability, level of soil salinity, depth of groundwater table, and irrigation facility, irrigation water availability, etc. suit them. According to Sival et al. (2009), the traditional method of salinity reclamation is to pond the field with water and to leach the salts from the soil by the sub-surface tile drainage systems. Tiles can be made of clay, concrete, plastic and other synthetic materials, such as high density polyethylene and polyvinylchloride. Presently, perforated synthetic pipes are used instead of earthen tiles which were popular in the past. The holes in the pipes are covered with thin sheets of fiber glass or spun nylon to avoid clogging and preventing inflow of soil so that

the system may be long lasting. The installation of tile drainage system is, however, relatively costly and may not be very effective in poorly permeable soils. Mole drains may be suitable for subsurface drainage of clay soils, but are not usually used for soil salinity reclamation because moles can collapse in coarse textured soils.

10.8 Management of Dryland Salinity

Dryland salinity is a serious problem in Western Australia and in the Great Plains region of North America. It occurs extensively in Canada in Manitoba, Saskatchewan and Alberta and in the United States in the states of Montana, North and South Dakota. Dryland salinity is also a problem in South Africa, Iran, Afghanistan, Thailand and India. These soils range in salinity from slightly saline to severe saline conditions. Soil salinity is a major problem in areas having low precipitation to evaporation ratio. Soluble salts released by the limited chemical weathering cannot be leached due to the scarcity of water. Saline seeps often develop in places where recharge areas have light textured soils having low moisture retention and high permeability but with an underlying impermeable layer. Seepage of saline water occurs somewhere at low points in the landscape. Long-term solutions to the problem of saline seeps should include land use changes with the objective of modifying the hydrological state. In addition, site specific treatments of salt-affected land are required to restore their productivity. Management practices for saline seeps should be aimed at increasing water use in the recharge areas to decrease the excess water seepage. This can be achieved by (i) intensive cropping for increased water use in the recharge area, (ii) growing deep rooted perennials that would draw water from greater depth of the soil, (iii) drainage in the recharge area, and (iv) growing salt tolerant crops in the seep area. The management options of dryland salinity of Australia were discussed systematically by CSIRO (2000).

10.9 Reclamation and Management of Sodic Soils

Several different approaches including chemical amendments, tillage operations, crop-management practices, hydrological manipulations, and electrical currents have been used to ameliorate sodic and saline-sodic soils (Qadir et al. 2007). A number of tillage options, such as deep plowing and sub-soiling have also been used to break up the shallow, dense, sodic clay pans and or natric horizons that occur within 0.4 m of the soil's surface (Abdelgawad et al. 2004). Management of sodic soils also requires leaching through irrigation and drainage, but before leaching, excess exchangeable sodium must be replaced by some suitable cation (Ca^{2+}) so that the ESP can be lowered to the desired level along with growing suitable crops. The replacement needs amendments that contain calcium or that produce calcium ions after application to the soil. A brief account of the conventional reclamation procedures is given below.

10.9.1 Crop Selection for Sodic Soils

It has long been known from classical agronomy literature that there are wide variations in the tolerance of crops to soil sodicity: rice (*Oryza sativa*) and dhaincha (*Sesbania aculeata*) appear to be tolerant, wheat (*Triticum aestivum*) and bajra (*Pennisetum typhoideum*) are only moderately tolerant and legume crops like mash (*Phaseolus mungo*) and lentil (*Lens culinaris*) are relatively sensitive to excess exchangeable sodium. A list of plants having some degree of tolerance to excess sodium and boron (usually high content in sodic soils) is given below:

Crops tolerant to high exchangeable sodium Karnal grass (*Diplachne fusca*)**,** rhodes grass (*Chloris gayana*), para grass (*Brachiaria mutica*), Bermuda grass (*Cynodon dactylon*), rice (*Oryza sativa*), dhaincha (*Sesbania aculeata*) and sugar beet (*Beta vulgaris*).

Crops semi-tolerant to high exchangeable sodium Wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*Avena sativa*), raya (*Brassica juncea*), senji (*Melilotus parviflora*), bajra (*Pennisetum typhoides*), cotton (*Gossypium hirsutum*), berseem (*Trifolium alexandrinum*), sugarcane (*Saccharum officinarum*).

Crops moderately tolerant to boron Cabbage (*Brassica oleracea capitata*), turnip (*B. rapa*), Kentucky bluegrass (*Poa pratensis*), barley (*Hordeum vulgare*), cowpea (*Vigna unguiculata*), oats (*Avena sativa*), corn (*Zea mays*), artichoke (*Cynara scolymus*), tobacco (*Nicotiana tabacum)*, mustard (*Brassica juncea*), clover, sweet (*Melilotus indica*), squash (*Cucurbita pepo*), muskmelon (*Cucumis melo*), and cauliflower (*B. oleracea botrytis*).

Crops tolerant to boron Alfalfa (*Medicago sativa*), purple vetch (*Vicia benghalensis*), parsley (*Petroselinum crispum*), red beet (*Beta vulgaris*), sugar beet (*B. vulgaris*), and tomato (*Lycopersicon lycopersicum*).

Crops very tolerant to boron (threshold values mg l^{-1} are given in parentheses) Sorghum (*Sorghum bicolor*) (7.4), cotton (*Gossypium hirsutum*) (6.0–10.0), celery (*Apium graveolens*) (9.8), and asparagus (*Asparagus officinalis*) (10.0–15.0).

A list of commercially available plant species tolerant to saline-sodic soils is prepared below on the basis of data of USDA-NRCS (2010).

Very highly tolerant Beardless wildrye, tall wheatgrass, altai wildrye, hybrid wheatgrass, slender wheatgrass and Russian wildrye.

Highly tolerant Tall fescue, western wheatgrass, fairway wheatgrass, crested wheatgrass, standard wheatgrass, Siberian wheatgrass, forage kochia, fourwing saltbush, winterfat and strawberry clover.

Moderately tolerant Creeping foxtail, meadow brome, smooth brome, pubescent wheatgrass, intermediate wheatgrass, thick spike wheatgrass, yellow sweet clover and Cicer milkvetch.

10.9.2 Amendments for Sodic Soils

Several chemical amendments have been used most extensively for the reclamation of sodic soils. Most common amendments include (i) soluble calcium compounds such as gypsum and calcium chloride which produce Ca^{2+} ions that replace exchangeable Na^{+} ions, (ii) sulfuric acid, and (iii) substances that produce sulfuric acid such as elemental sulfur, pyrite, ferrous sulfate, and aluminium sulfate. Sulfuric acid thus formed reacts with insoluble calcium carbonate commonly found in sodic soils and release soluble Ca^{2+} ions. The reactions of the various amendments and their mechanism of action are shown below.

Gypsum
Gypsum reacts with both Na2CO3, and adsorbed sodium as follows:

$$Na_2CO_3 + CaSO4 = CaCO_3 + Na_2SO_4\,(\text{leachable})$$

$$Na - Clay - Na + CaSO_4 = Ca - Clay + Na_2SO_4\,(\text{leachable})$$

Calcium chloride
Calcium chloride (CaCl2.2H2O) is a highly soluble salt which supplies soluble calcium directly. Its reactions in sodic soil are similar to those of gypsum.

$$Na_2CO_3 + CaCl_2 = CaCO_3 + 2NaCl\,(\text{leachable})$$

$$Na - Clay - Na + CaCl = Ca - Clay + 2NaCl\,(\text{leachable})$$

Sulfuric acid
Upon application of sulfuric acid (H2SO4) to soils containing calcium carbonate, it immediately reacts to form calcium sulfate and thus provides soluble calcium indirectly.

$$Na_2CO_3 + H_2SO_4 = CO_2 + H_2O + Na_2SO_4\,(\text{leachable})$$

$$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$$

$$Na - Clay - Na + CaSO_4 = Ca - Clay + Na_2SO_4\,(\text{leachable})$$

Iron sulfate and aluminium sulfate

Both of iron sulfate (FeSO4.7H2O) and aluminium sulfate [Al2(SO4)3.18H2O] are solid granular materials soluble in water. When applied to soils, these compounds hydrolyze to form sulfuric acid.

$$FeSO_4 + 2H_2O = H_2SO_4 + Fe(OH)_2$$

$$H_2SO_4 + CaCO_3 = CaSO_4 + H_2O + CO_2$$

$$Na - Clay - Na + CaSO_4 = Ca - Clay + Na_2SO_4\,(\text{leachable})$$

Aluminium sulfate acts similarly.

Sulfur

Sulfur (S) is not soluble in water and does not supply calcium directly for replacement of adsorbed sodium. When applied to soils, sulfur undergoes oxidation to form sulfuric acid and gives reactions as shown below:

$$2S + 3O_2 = 2SO_3$$

$$SO_3 + H_2O = H_2SO_4\,(\text{Sulfuric acid performs as above})$$

Pyrite

Pyrite (FeS2) is another possible amendment for sodic soil reclamation. The following series of reactions occur after applying pyrite to soil:

$$\text{Step I.} 2FeS_2 + 2H_2O + 7O_2 = 2FeSO_4 + 2H_2SO_4$$

$$\text{Step II.} 4\,FeSO_4 + O_2 + 2\,H_2SO_4 = 2\,Fe_2(SO_4)_3 + 2\,H_2O$$

$$\text{Step III.} Fe_2(SO_4)_3 + FeS_2 = 3\,FeSO_4 + 2\,S$$

$$\text{Step IV.} 2\,S + 3\,O_2 + 2\,H_2O = 2\,H_2SO_4\,(\text{Sulfuric acid performs as above})$$

The choice of an amendment depends on (a) relative effectiveness as judged from the improvement of soil properties and crop growth, (b) relative costs involved, (c) the risk of handling materials, and (d) time required for an amendment to react in the soil and effectively replace adsorbed sodium. Sulfuric acid reacts immediately with the soil calcium carbonate to release soluble calcium for exchange with sodium. Elemental sulfur must be oxidized by soil bacteria and react with water to form sulfuric acid. The formation of sizeable amounts of sulfuric acid from elemental sulfur may take several months to several years. Sulfur, sulfuric acid, iron sulfate, and aluminum sulfate do not supply calcium. They are useful for reclamation only when the soil contains lime. When the soil to be reclaimed does not contain enough lime, gypsum or materials that contain calcium are to be used. Iron and

aluminium sulfates are usually too costly and have not been used for any large-scale improvement of sodic soils in the past. Because amendments like sulfur and pyrite must first be oxidized in soil to sulfuric acid, the amendments are relatively slow acting. Being the cheapest and most abundantly available, gypsum is the most widely used amendment.

There were some studies earlier to compare the effectiveness of various amendments at improving the physical and chemical properties of saline sodic and sodic soils (Amezketa et al. 2005; Hanay et al. 2004). The relative effectiveness of gypsum and sulfuric acid has received the most attention because they are widely used as reclamation amendments. Recently, crops, crop residues or industrial effluents and synthetic polymers have been included in efficiency studies (Hanay et al. 2004). Gypsum, as mentioned above, is the most commonly used amendment due to its availability and low cost (Joachim et al. 2007), but it is slow in reaction. However, its efficiency can be increased if applied at variable rates according to the gypsum requirements of the soil. According to Barros et al. (2004), application of gypsum and a mixture of gypsum and limestone were more efficient for combating soil sodicity. Agar (2011) used polyphosphogypsum (PG) as amendment to reclaim saline and sodic soils in Turkey. He added a total of 7.5 and 15.0 t PG ha^{-1} in divided doses to the field plots of 100 m^2 in three consecutive years. Results showed that the cultivation process and plant roots contributed to the improvement of soil physical and chemical properties. Application of 7.5 and 15.0 t PG ha^{-1} in divided doses respectively caused soil improvement 10 and 8 times more than gypsum treatments. Moreover, leaching 50% of the soluble salt from the soil profile required a depth of leaching water approximately 2.3 times of soil depth to be reclaimed. Divided doses of PG amendments resulted in a better reclamation process. Prapagar et al. (2012) conducted a pot experiment on saline-sodic soil in Sri Lanka with some amendments to compare their abilities of improving soil quality parameters. The treatments were: T1-control (no amendment), T2–1% cow dung (CD), T3–1% partially burnt paddy husk (PH), T4-gypsum (GYP) (100% Gypsum Requirement), T5–1% CD + GYP, T6–1% PH + GYP. The amendments T2 to T6were applied on the soil surface and incubated at room temperature (31 ± 1 °C) for 90 days. After incubation, leaching was done for 42 days with 3 liter water per pot at 7 days intervals up to 6 cycles. After incubation and leaching of soils, onion variety Wallara-60 was grown in these pots. Results showed significant differences in bulk density, electrical conductivity (EC), pH, exchangeable Ca^{2+} and SAR among the treatments in comparison to the control. The highest reduction in SAR and EC were recorded in the treatment GYP + PH (T6). Yield of onion was also the highest in this treatment. Joachim et al. (2007) observed beneficial effect of the combined use of farm yard manure (FYM) and GYP on the reclamation of sodic soils. Equivalent quantities of some amendments for sodic soils are given in Table 10.10.

Amount of Amendments

The quantity of an amendment for sodic soil reclamation depends on the quantity of exchangeable sodium to be replaced. This will also depend on soil texture and mineralogical make up, exchangeable sodium percentage (ESP) and the crops to be

Table 10.10 Equivalent quantities of some amendments

Amendment	Relative quantity[a]
Gypsum ($CaSO_4$ $2H_2O$)	1.00
Calcium chloride ($CaCl_2$ 2 H_2O)	0.85
Sulphuric acid (H_2SO_4)	0.57
Iron sulphate ($FeSO_4$.7 H_2O)	1.62
Aluminium sulfate (Al_2 $(SO_4)_3$.18 H_2O)	1.29
Sulphur (S)	0.19
Pyrite (FeS_2) – 30% sulphur	0.63
Calcium polysulfide (CaS_5) – 24% sulfur	0.77

[a]These quantities are based on 100 percent pure materials. If the material is not 100 percent pure, necessary correction must be made. Thus, if gypsum is only 80 percent pure. $1.0 \times (100 \div 80) = 1.25$, the quantity to be added will be 1.25 ton instead of 1.00 ton.

grown. The relative tolerance of a crop to exchangeable sodium and its normal rooting depth will largely determine the soil depth up to which excess adsorbed sodium must be replaced for satisfactory crop growth. Replacement of each mole of adsorbed sodium per 100 g soil will require half a mole of soluble calcium. The quantity of pure gypsum required to supply half a cmol of calcium per kg soil for the upper 15 cm soil depth will be

$$\frac{\text{molecular weight of gypsum}}{200} = \frac{172}{200} = 0.86 \text{ g kg}^{-1} \text{ soil}$$
$$= 86 \text{ x } 10^{-5} \text{ kg kg}^{-1} \text{soil}$$
$$= 86 \text{ x } 10^{-5} \text{ x } 2.24 \text{ x } 10^{6} \text{ kg ha}^{-1}$$
$$= 1926 \text{ kg or } 1.96 \text{ t ha}^{-1}$$

If it is desired to replace greater quantities of adsorbed sodium, the quantity of gypsum can be accordingly increased.

Gypsum requirement

The quantity of gypsum required for reclaiming a sodic soil is termed as the gypsum requirement (GR). The GR test is performed by mixing a small soil sample (5 g) with a relatively large volume of saturated gypsum solution and measuring the calcium lost from the solution after reaction with the soil. The decrease in calcium from the solution can be expressed on the basis of tons of $CaSO_4.2H_2O$ per hectare 30 cm of soil. Many sodic soils contain appreciable amounts of soluble sodium carbonate in addition to excess exchangeable sodium. In such cases, the gypsum requirement test evaluates the amount of calcium required to replace the exchangeable sodium plus the amount required to neutralize all the soluble sodium carbonate

in the soil. Gypsum is usually applied on the soil surface and leached, only a small fraction of the soluble carbonates reacts with applied calcium and a major fraction of the soluble carbonates are leached without reacting with applied gypsum. It does not seem necessary to add extra gypsum to neutralize soluble carbonates. Gypsum requirement can also be calculated by the following formula (Horneck et al. 2007).

$$\mathrm{GR} = \left(\text{present ESP} - \text{desired ESP}\right) \mathrm{x}\, \mathrm{CEC}\, \mathrm{x}\, 0.021$$

The factor of 0.021 assumes CEC is in meq/100 g or cmol (+charge) kg^{-1} units.

Method of application

Gypsum and other amendments except sulfuric acid can be applied by broadcasting on the surface and then incorporating within a shallow depth by disking or plowing. It is more effective than spreading gypsum only on the surface. When the problem of exchangeable sodium is only mild, gypsum applied in dissolved form was found more beneficial for the establishment of pasture in comparison to soil application treatments. Deep plowing (up to 100 cm) has been reported to be a useful practice for improving sodic soils with hardpans or dense clay subsoil layers. The success of deep plowing chiefly depends on the mixing of low-clay calcareous or gypsiferous subsoil material with high-clay B horizon material to provide a more favorable physical matrix for water movement and root penetration and to provide a source of calcium for replacement of exchangeable sodium in the profile.

Leaching a sodic soil after amendment needs more water than a saline soil because (i) chemical amendments, except sulfuric acid and calcium chloride, are less soluble than salts in soil, and (ii) sodic soils are generally less permeable than saline soils. Amelioration of sodic and saline-sodic soils with high clay content, particularly where montmorillonite is the dominant clay mineral, is technically difficult and expensive. When water is applied for leaching, the clay swells rapidly, destroying the macro-pores which provide the primary drainage pathways. The hydraulic conductivity of the fully saturated soil is usually very low and drainage cannot be provided at economic spacing (Qureshi et al. 2007). Naseri and Rycroft (2002) found that extensive swelling occurred when low salinity water (EC = 0.5 dS m^{-1}, SAR = 0.6) was used for leaching. Increasing calcium concentration in the leaching water reduced swelling during the leaching process, and controlled the dispersion.

Particle size of ground gypsum

After collecting gypsum from natural deposits it is finely ground for applying in crop fields. It is held that the finer the particles of gypsum, the more effective it is for the reclamation of sodic soils. Treatment of soil with very finely ground gypsum results in high initial hydraulic conductivity which decreased sharply with time. But treatment with 2 mm mesh gypsum helped in maintaining permeability at a higher level and for a longer period. Their results showed that higher solubility of finer particles caused them to react with free sodium carbonate, inactivating the soluble calcium due to the formation of insoluble calcium carbonate.

Organic amendments

It has been already mentioned that some organic amendments are used for reclaiming sodic and saline-sodic soils. For example, Prapagar et al. (2012) observed that the addition of organic amendments to soils is highly accepted by the farmers. Reclamation systems involving composts, green manures, crop rotation and other biological agents are termed as biodynamic systems by Ansari and Ismail (2008). In comparison to the conventional methods, biodynamically managed soils have better physical, chemical and biological properties. Often organic amendments are used in addition to gypsum (Mohamed and Abdel-Fattah 2012). Application with 10 t ha^{-1} FYM in combination with chemical amendments improved soil physical properties like bulk density, porosity, void ratio, water permeability and hydraulic conductivity and enhanced rice and wheat yields in sodic soil (Hussain et al. 2001). Other organic materials like rice straw, wheat straw, rice husk and chopped salt grass also improved these physical properties of a saline sodic soil.

Pressmud

Pressmud, also known as filter cake or filter mud, is produced in sugar mills through sedimentation of the suspended materials such as fiber, sugar, wax, ash, soil and other particles from the cane juice (Muhammad and Khattak 2009). It has been used as an ameliorant in sodic and saline-sodic soils (Barry et al. 2001). The pressmud contains considerable amount of sulfate, extracted by the method of sulfidation is called sulfidation pressmud cake. Pressmud, which contains high amount of carbonates, is extracted by the method of carbonation and is known as carbonated pressmud cake. Pressmud usually contains about 70% lime, 15–20% organic matter and 2–3% sugar (Khattak and Khan 2004). The ash comprises of oxides of Si, Ca, P, Mg and K (Partha and Sivasubramanian 2006). The organic matter is highly soluble and readily available for microbial activity and, therefore, to the soil (Rangaraj et al. 2007). Carbon dioxide produced through microbial activity may increase the solubility of lime and hence its effectiveness in reclaiming saline-sodic soils (Qadir et al. 2006). Some investigators have observed an increase in yields of various crops including maize and millet with pressmud applications (Rangaraj et al. 2007; Elsayed et al. 2008) and an improvement in soil physical, chemical and biological conditions (Barry et al. 2001).

10.9.3 Phytoremediation of Sodic Soils

The amelioration of saline, saline-sodic, sodic and calcareous sodic soils can be done by using some plants, crops or cropping systems. This is known as phytoremediation. Qadir et al. (2007) reviewed phytoremediation of sodic soils, and they pointed out that experiments with various cropping systems and on different soils for phytoremediation began in 1920s. The overall decrease in ESP under the phytoremediation treatment may even be greater than that obtainable with gypsum.

Various cropping systems have been used. The mechanism of action of the crop plants involves the physical action of roots to modify soil aggregation, porosity and permeability, root respiration producing CO_2, enhanced proton in the root zone, production of H_2CO_3, and dissolution of native $CaCO_3$ releasing Ca^{2+} ions that replaces Na^+ ions from clay surfaces. Dissolution and precipitation kinetics of calcite are determined by the chemistry of the system. A typical reaction for the dissolution of calcite may be expressed as a function of CO_2 in the root zone:

$$CaCO_3 + CO_2 + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^-$$

The reaction is the resultant of three processes which occur concurrently: (1) conversion of CO_2 in soil solution into H_2CO_3 and its reaction with $CaCO_3$ (2) dissociation of H_2CO_3 into H^+ and HCO_3^- and the reaction of H^+ with $CaCO_3$ (3) dissolution of $CaCO_3$ resulting in Ca^{2+} and CO_3^{2-} .

$$CaCO_3 + H_2CO_3 \Leftrightarrow Ca^{2+} + 2HCO_3^-$$

$$CaCO_3 + H^+ \Leftrightarrow Ca^{2+} + HCO_3^-$$

$$CaCO_3 + H_2O \Leftrightarrow Ca^{2+} + CO_3^{2-} + H_2O$$

Amelioration takes place by all these processes if adequate leaching can be provided. Since phytoremediation ameliorates the root zone, alternating crops of differential root habit should be included in the crop sequence (Akhter et al. 2003). Again, deep-rooted crops have advantages in terms of greater depth of soil amelioration. For example, alfalfa roots can penetrate as deep as 1.2 m in the soil.

10.9.4 Management of Calcareous Saline-Sodic Soils

In calcareous (soils that effervesce upon addition of dilute HCl) saline-sodic soils, the free calcium carbonate can contribute little to the replacement of Na + ions because the calcium carbonate is insoluble in water. Instead of supplying Ca^{2+} ions by the addition of gypsum, the native calcium carbonate in these soils can be dissolved to release soluble Ca^{2+} ions that would replace exchangeable Na+. This can be achieved by (i) addition of sulfuric acid or sulfur, and (ii) biological production of carbonic acid through root and microbial respiration. The products of the reaction of $CaCO_3$ and sulfuric acid are CO_2, H_2O, SO_4^{2-}, and Ca^{2+}. The Ca^{2+} ions replace exchangeable Na^+, reduces the ESP and act as a flocculant. Any acid can dissolve soil $CaCO_3$ and release the bound Ca. Sulfuric acid is most common because it is relatively inexpensive and adds less salt to the soil. Elemental sulfur is converted to sulfuric acid by sulfur oxidizing bacteria, producing the same effect as sulfuric acid. Sulfur conversion is a biological process, however, and requires several weeks to months to take place unlike acids, which react instantly. The phytoremediation technique has been discussed in the preceding section.

10.9.5 Fertilizers for Sodic Soils

Low organic matter content, high pH and low biological activity are responsible for the general deficiency of available nitrogen in sodic soils. Considerable volatilization losses of N as ammonia may occur due to their high pH. Poor soil structure and high pH also adversely affect the transformations and availability of applied nitrogenous fertilizers, such as hydrolysis of applied urea. It is generally recommended that crops grown in sodic soils be fertilized at 25 percent excess over the rates recommended for normal soils. Sodic soils generally contain high amounts of extractable phosphorus and crops usually do not respond to applied P. Presence of sodium carbonate in these soils results in the formation of soluble sodium phosphates. However, if the soil contains significant amounts of sodium carbonate most of the soil calcium is in the calcium carbonate form and not available to the plants. Increasing soil sodicity was found to result in reduced uptake of potassium by most crops. Sodicity nearly always results in an increased uptake of sodium and decreased uptake of calcium by plants. When the exchangeable sodium levels are very high, calcium is often the first limiting nutrient. Without amendments, calcium limitation is difficult to be corrected. High pH, low organic matter content and presence of calcium carbonate strongly modify the availability of micronutrients to plants grown in sodic soils. Zinc deficiency has been widely reported for crops grown in sodic soils. Application of 10 kg $ZnSO_4 ha^{-1}$may mitigate the deficiency of Zn in rice grown in an amended, highly sodic soil. Iron and manganese may also become deficient in sodic soils. Addition of iron and manganese salts to correct the deficiency may not be useful without changing the oxidation state by submergence.

10.10 Environmental Impact of Saline Soil Reclamation

Soil reclamation refers to the mechanical, chemical or biological eradication of the problem(s) a soil poses to a particular use. Scrapping of salt-crust, removal of excess soluble soils by leaching and removing soil acidity by liming are some examples of soil reclamation. Since soil problems are use-oriented, we can often avoid reclamation by adopting an alternative use or an innovative but sustainable management practice. Soil reclamation is usually large scale operations involving time and money for heavy machineries, chemicals, and labors. Reclamation of saline and sodic soils requires construction of bunds, ponding of water, treatment with gypsum or other soil modifiers, and installations of suitable irrigation and drainage systems. It also needs the modification of the existing environmental settings so that salinity/sodicity does not develop again. So, reclamation of saline and sodic soils may often cause drastic effects on the ecosystems (Wang et al. 2014). After an area is reclaimed and developed, intensification and diversification of cropping increase along with an increased use of agrochemicals, including fertilizers, soil modifiers and pesticides. Construction of industrial, commercial and recreational facilities

(Hadley 2009) causes significant alteration in landscape and ecosystem functionality (Lie et al. 2008). These alterations may profoundly impact physical and chemical properties of soil and water (Sun et al. 2011). Salts and nutrients leached down to the groundwater table may find their way to nearby lakes and streams and pollute them. Chemicals used to reclaim sodic soils and the metals mobilized by saline and sodic soil reclamation may degrade sediment-groundwater system (Chen and Jiao 2008). These changes are noticed over several decades following reclamation (Cui et al. 2012).

Study Questions

1. Explain the criteria classifying salt affected soils. Give an account of the distribution of salt affected soils. Write down the characteristics of saline, sodic and saline sodic soils.
2. Describe the effects of soil salinity and sodicity on plants. Mention some salt sensitive and salt tolerant crop plants with their threshold ECe values.
3. Cite the principles of saline soil management. Discuss leaching as the process of salinity reclamation.
4. What chemical substances are used as amendments of sodic soils? How can you measure the suitability of an amendment?
5. Write notes on (a) saline seeps, (b) organic amendments for sodic soil, (c) chloride and boron tolerant plants, (d) nutrient deficiency and toxicity in high pH soils, and (e) phytoremediation of sodic soils.

References

Abdelgawad A, Arslan A, Awad F, Kadouri F (2004) Deep plowing management practice for increasing yield and water use efficiency of vetch, cotton, wheat and intensified corn using saline and non-saline irrigation water. Proceedings of the 55th IEC Meeting of the International Commission on Irrigation and Drainage (ICID), September 9–10, 2004, Moscow, Russia

Agar AI (2011) Reclamation of saline and sodic soil by using divided doses of phosphogypsum in cultivated condition. Afr J Agric Res 6(18):4243–4252

Akhter J, Mahmood K, Malik KA, Ahmed S, Murray R (2003) Amelioration of a saline sodic soil through cultivation of a salt-tolerant grass *Leptochloafusca*. Environ Conserv 30:168–174

Akramkhanov A, Sommer R, Martius C, Hendrickx JMH, Vlek PLG (2008) Comparison and sensitivity of measurement techniques for spatial distribution of soil salinity. Irrig Drain Syst 22:115–126

Amezketa E, Aragüés R, Gazol R (2005) Efficiency of Sulfuric Acid, Mined Gypsum, and Two Gypsum By-Products in Soil Crusting Prevention and Sodic Soil Reclamation. Agronomy Journal 97(3):983–989

Amiri B, Assareh MH, Jafari M, Rasuoli B, Arzani B, Jafari AA (2010) Effect of salinity on growth, ion content and water status of glasswort (Salicorniaherbacea L.) Caspian J Env Sci 8(1):79–87

Anon (2015) Trees and shrubs that tolerate saline soils and salt spray drift. Publication 430–031, College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University, www.ext.vt.edu

Ansari AA, Ismail SA (2008) Biodynamic management in sodic soils. J Soil Nature 2(2):01–04

Ashraf M (2001) Relationships between growth and gas exchange characteristics in some salt-tolerant amphidiploid Brassica species in relation to their diploid parents. Environ Exp Bot 45:155–163

Ashraf M (2009) Biotechnological approach of improving plant salt tolerance using antioxidants as markers. Biotech Adv 27:84–93

Aslam M, Prathapar SA (2006). Strategies to mitigate secondary salinization in the Indus Basin of Pakistan: A Selective Review. Research Report 97. International Water Management Institute (IWMI), Colombo, Sri Lanka

Ayers RS, Westcot DW (1985) Water quality for agriculture. FAO Irrigation and Drainage Paper 29. Food and Agriculture Organization of the United Nations, Rome

Azizi M, Chehrazi M, Zahedi SM (2011) Effects of salinity stress on germination and early growth of sweet William (*Dianthus barbatus*). Asian J Agric Sci 3(6):453–458

Balibrea ME, Cuartero J, Bolarín MC, Pérez-Alfocea F (2003) Activities during fruit development of *Lycopersicon* genotypes differing in tolerance salinity. Physiol Plant 118:38–46

Barros MFC, Fontes MPF, Alvarez VVH, Ruiz HA (2004) Reclamation of salt-affected soils in Northeast Brazil with application of mined gypsum and limestone. Revista Brasileira de Engenharia Agricola e Ambiental 8(1):59–64

Barry GA, Rayment GE, Jeffery AJ, Price AM (2001) Changes in cane soil properties from application of sugar mill by-products. Proceeding Conference of the Australian Society of Sugarcane Technology. Mackay, Queensland

Bauder JW, Brock TA (2001) Irrigation water quality, soil amendment, and crop effects on sodium leaching. Arid Land Res Manag 15:101–113

Bayuelo-Jiménez JS, Debouck GD, Lynch JP (2003) Growth, gas exchange, water relations, and ion composition of *Phaseolus* species grown under saline conditions. Field Crop Res 80:207–222

Botia P, Navarro JM, Cerda A, Martinez V (2005) Yield and fruit quality of two melon cultivars irrigated with saline water at different stages of development. Eur J Agron 23:243–253

Chaum S, Pokasombat Y, Kirdmanee C (2011) Remediation of salt affected soil by gypsum and farmyard manure−importance for the production of jasmine rice. Aust J Crop Sci 5:458–465

Chen K, Jiao JJ (2008) Metal concentrations and mobility in marine sediment and groundwater in coastal reclamation areas: a case study in Shenzhen, China. Environ Pollut 151(3):576–584

Chengrui M, Dregne HE (2001) Silt and the future development of China's Yellow River. Geogr J 167:7–22

Chinnusamy V, Jagendorf A, Zhu JK (2005) Understanding and improving salt tolerance in plants. Crop Sci 45:437–448

Corwin DL, Rhoades JD, Simunek J (2007) Leaching requirement for soil salinity control: steady-state versus transient models. Agric Water Manag 9:65–180

CSIRO (2000) Management of dryland salinity: future strategic directions. Primary Industries Report Series 78, CSIRO Publishing, PO Box 1139 (150 Oxford Street), Collingwood, Australia

Cui J, Liu C, Li Z, Wang L, Chen X, Ye Z, Fang C (2012) Long-term changes in topsoil chemical properties under centuries of cultivation after reclamation of coastal wetlands in the Yangtze Estuary, China. Soil Tillage Res 123:50–60

del Amor FM, Martinez V, Cerda A (2001) Salt tolerance of tomato plants as affected by stage of plant development. Hort Sci 36:1260–1263

Dhanapackiam S, Ilyas MHM (2010) Effect of salinity on chlorophyll and carbohydrate contents of Sesbania grandiflora seedlings. Indian J Sci Technol 3(1):64–66

Dong H (2012) Technology and field management for controlling soil salinity effects on cotton. AJCS 6(2):333–341

Elsayed MT, Babiker MH, Abdelmalik ME, Mukhtar ON, Montange D (2008) Impact of filter mud application on the germination of sugarcane and small-seeded plants and on soil and sugarcane nitrogen contents. Bioresour Technol 99:4164–4168

EPA (2004) Guidelines for Water Reuse, September 2004, EPA/625/R-04/108, Environment Protection Agency, USA

Essa TA (2002) Effect of salinity stress on growth and nutrient composition of three soybean (Glycine max L. Merrill) Cultivars. J Agron Crop Sci 188(2):86–93
Ewase ASS, Omran S, El-Sherif S, Tawfik N (2013) Effect of salinity stress on coriander (*Coriandrum sativum*) seeds germination and plant growth. Egypt Acad J BiolSci 4(1):1–7
Falstad J (2000) Soil condition. transplant status in Burger Draw. Billings Gazette. Prepared by D.G. Steward Page. Burger Draw Comments and Recommendations. 6/06/00
FAO (2002) Global network on integrated soil management for sustainable use of salt-affected soils. FAO Land and Plant Nutrition Management Services, Rome, Italy
FAO (Food and Agricultural Organization of the United Nations) (2006) TerraSTAT database. At: <http://www.fao.org/ag/agl/agll/terrastat/>
Flagella Z, Cantore V, Giuliani MM, Tarantio E, De Caro A (2002) Crop salt tolerance physiological, yield and quality aspects. Rec Res Dev Plant Biol 2:155–186
Garg N, Singla R (2004) Growth, photosynthesis, nodule nitrogen and carbon fixation in the chickpea cultivars under salt stress. Braz J Plant Physiol 16(3):137–146
Garg VK, Malhotra S (2008) Response of *Nigella sativa* L. to fertilizers under sodic soil condition. J Med Aromat Plant Sci 30:122–125
Ghoulam C, Foursy A, Fares K (2002) Effects of salt stress on growth, inorganic ions and proline accumulation in relation to osmotic adjustment in five sugar beet cultivars. Environ Exp Bot 47:39–50
Gomez JM, Jimenz A, Olmas E, Sevilla F (2004) Location and effects of long-term NaCl stress on superoxide dismutase and ascorbate peroxidase isoenzymes of pea (*Pisum sativum* cv. Puget) chloroplasts. J Exp Bot 55:119–130
Gregory PJ, Nortcliff S (2013) Soil conditions and plant growth. Wiley Blackwell, New York
Gupta RK, Abrol IP (2000) Salinity build-up and changes in the rice-wheat system of the Indo-Gangetic Plains. Exp Agric 36:273–284
Hadley D (2009) Land use and the coastal zone. Land Use Policy 26S:S198–S203
Hanay A, Büyüksönmez F, Kızıloglu FM, Canbolat MY (2004) Reclamation of saline-sodic soils with gypsum and MSW compost. Compos Sci Utili 12:175–179
Hanson BR, May DM (2004) Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity and profitability. Ag Water Mgt 68:1–17
Haque SA (2006) Salinity problems and crop production in coastal regions of Bangladesh. Pak J Bot 38(5):1359–1365
Hernandez JA, Ferrer MA, Jimenez A, Barcelo AR, Sevilla F (2001) Antioxidant systems and O^{2-}/H_2O_2 production in the apoplast of pea leaves. Its relation with salt-induced necrotic lesions in minor veins. Plant Physiol 127:817–831
Higbie SM, Wang F, McD SJ, Sterling TM, Lindemann WC, Hughs E, Zhang J (2010) Physiological response to salt (NaCl) stress in selected cultivated tetraploid cottons. Int. J Agron 1:1–12
Horneck DA, Ellsworth JW, Hopkins BG, Sullivan DM, Stevens RG (2007) Managing salt-affected soils for crop production. A Pacific Northwest Extension publication Oregon State University, University of Idaho, Washington State University
Hussain N, Hassan G, Arshadullah M, Mujeeb F (2001) Evaluation of amendments for the improvement of physical properties of sodic soil. Int J Agric Biol 3:319–322
Jamali LA, Ibupoto KA, Chattah SH (2012) Effects of salt leaching on soil under different irrigation amounts and intervals. Sixteenth International Water Technology Conference, IWTC 16 2012, Istanbul, Turkey
Jamil A, Riaz S, Ashraf M, Foolad MR (2011) Gene expression profiling of plants under salt stress. Crit Rev Plant Sci 30(5):435–458
Joachim HJR, Makoi P, Ndakidemi A (2007) Reclamation of sodic soils in northern Tanzania, using locally available organic and inorganic resources. African J Biotech 6(16):1926–1931
Kang DJ, Endo A, Seo YJ (2013) Effect of soil scraping on the reclamation of tsunami-damage paddy soil. J crop Sci. Biotech 16(3):219–223
Kara T, Willardson LS (2006) Leaching requirements to prevent soil salinization. J Applied Sci 6(7):1481–1489

Karlberg L (2005) Irrigation with saline water using low-cost drip-irrigation systems in sub-Saharan Africa. PhD Thesis, KTH Architecture and the built environment, Stockholm, Sweden
Khan MA, Duke NC (2001) Halophytes- a resource for the future. Wetl Ecol Manag 6:455–456
Khattak RA, Khan RJ (2004) Evaluation, reclamation and management of saline sodic soils in Kohat division. Final Report. Deptartment of Soil and Environmental Sciences, NWFP Agriculture University Peshawar. National Drainage Programme (NDP), Govt of Pakistan
Khorsandi F, Anagholi A (2009) Reproductive compensation of cotton after salt stress relief at different growth stages. J Agron Crop Sci 195:278–283
Khoshgoftarmanesh AH, Shariatmadari H, Vakil R (2003) Reclamation of saline soils by leaching and barley production. Commun Soil Sci Plant Anal 34(19–20):2875–2883
Lie HJ, Cho CH, Lee S, Kim ES, Koo BJ, Noh JH (2008) Changes in marine environment by a large coastal development of the Saemangeum Reclamation Project in Korea. Ocean and. Polar Res 30(4):475–484
Lobell DB, Ortiz-Monsterio JI, Gurrola FC, Valenzuuela L (2007) Identification of saline soils with multiyear remote sensing of crop yields. Soil Sci Soc Am J 71:777–783
Maghsoudi AM, Maghsoudi K (2008) Salt stress effect on respiration and growth of germinated seeds of different Wheat (*Triticum aesativum* L.) cultivars. World J Agri Sci 4(3):351–358
Mansour MM (2000) Nitrogen containing compounds and adaptation of plants to salinity stress. Biol Plant 43:491–500
Martinez-Beltran J, Manzur CL (2005) Overview of salinity problems in the world and FAO strategies to address the problem. Proceedings of the International Salinity Forum, April 2005, Riverside, California
Metternicht GI, Zinck JA (2003) Remote sensing of soil salinity: potentials and constraints. Remote Sens Environ 85:1–20
Mohamed K, Abdel-Fattah (2012) Role of gypsum and compost in reclaiming saline-sodic soils. IOSR J Agric Vet Sci 1(3):30–38
Moradi P, Zavareh M (2013) Effects of salinity on germination and early seedling growth of chickpea (*Cicer arietinum* L.) cultivars. Intl J Farm Alli Sci 2(3):70–74
Mudgal V, Madaan N, Mudgal A, Mishra S (2009) Changes in growth and metabolic profile of Chickpea under salt stress. J Appl Biosci 23:1436–1446
Mudgal V, Madaan N, Mudgal A, Singh A, Kumar P (2010) Comparative study of the effects of salinity on plant growth, nodulation, and Legheamoglobin Content in Kabuli and Desi Cultivars of *Cicer arietinum* (L.). KBM. J Biol 1:1–4
Muhammad D, Khattak RA (2009) Growth and nutrient concentrations of maize in pressmud treated saline-sodic soils. Soil Environ 28(2):145–155
Munns R (2005) Genes and salt tolerance: bringing them together. Tansley rev. New Phytol 167:645–663
Naseri AA, Rycroft D (2002) Effect of swelling and overburden weight on hydraulic conductivity of a restructured saline sodic clay. Paper presented at the 17th World Congress of Soil Science, 14–21 August 2002, Bangkok, Thailand
Naseri R, Emami T, Mirzaei A, Soleymanifard A (2012) Effect of salinity (sodium chloride) on germination and seedling growth of barley (Hordeum Vulgare vulgare L.) cultivars. Int J Agric Crop Sci 4(13):911–917
Nasser JY, Sholi C (2012) Effect of salt stress on seed germination, plant growth, photosynthesis and ion accumulation of four tomato cultivars. Am J Plant Physiol 7:269–275. American
Ondrasek G, Romic D, Rengel Z, Romic M, Zovko M (2009) Cadmium accumulation by muskmelon under salt stress in contaminated organic soil. Sci Tot Enviro 407:2175–2182
Oster JD, Grattan SR (2002) Drainage water reuse. Irrig Drain Syst 16:297–310
Oster JD, Wichelns D (2003) Economic and agronomic strategies to achieve sustainable irrigation. Irrig Sci 22:107–120
Parida AK, Das AB (2005) Salt tolerance and salinity effects on plants. A review. Ecotox Environ Safety 60:324–349

Partha N, Sivasubramanian V (2006) Recovery of chemicals from pressmud- A sugar industry waste. Indian Chem Eng Section 48(3):160–163
Parvaiz A, Satyawati S (2008) Salt stress and phyto-biochemical responses of plants – a review. Plant Soil Environ 54:89–99
Patel BB, Patel Bharat B, Dave RS (2011) Studies on infiltration of saline–alkali soils of several parts of Mehsana and Patan districts of north Gujarat. J Appl Technol Environ Sanit 1(1):87–92
Pitman MG, Lauchli A (2002) Global impact of salinity and agricultural ecosystems. In: Lauchli A, Luttge U (eds) Salinity: environment – plants – molecules. Kluewer Academic Publishers, Dordrecht
Prapagar K, Indraratne SP, Premanandharajah P (2012) Effect of soil amendments on reclamation of saline-Sodic soil. Trop Agric Res 23(2):168–176
Qadir M, Noble MD, Schubert S, Thomas RJ, Arslan A (2006) Salinity induced land degradation and its sustainable management: problems and prospects. Land Degrad Dev 17:661–676
Qadir M, Oster JD (2004) Crop and irrigation management strategies for saline-sodic soils and water aimed at environmentally sustainable agriculture. Sci Total Environ 323:1–19
Qadir M, Oster JD, Schubert S, Noble AD, Sahrawat KL (2007) Phytoremediation of sodic and saline-sodic soils. Adv Agron 96:197–247
Qadir M, Wichelns D, Raschid-Sally L, McCornick PG, Drechsel P, Bahri A, Minhas PS (2010) The challenges of wastewater irrigation in developing countries. Agric Water Manag 97:561–568
Qureshi AS, Qadir M, Heydari N, Turral H, Javadi A (2007) A review of management strategies for salt-prone land and water resources in Iran.International Water Management Institute, IWMI Working Paper 125, Colombo, Sri Lanka
Radi AA, Farghaly FA, Hamada AM (2013) Physiological and biochemical responses of salt-tolerant and salt-sensitive wheat and bean cultivars to salinity. J Biol Earth Sci 3(1):B72–B88
Rangaraj T, Somasundaram E, Amanullah MM, Thirumurgan V, Ramesh S, Ravi S (2007) Effect of Agro-industrial wastes on soil properties and yield of irrigated finger millet (*Eleusine coracana* L. Gaertn) in coastal soil. Res J Agric Biol Sci 3(3):153–156
Rengasamy P (2006) World salinization with emphasis on Australia. J Exp Bot 57:1017–1023
Richards LA (1954) Diagnosis and improvements of saline and alkali soils. USDA Agriculture Handbook 60. USA
Romero-Aranda R, Soria T, Cuartero S (2001) Tomato plant-water uptake and plant-water relationships under saline growth conditions. Plant Sci 160:265–272
Sadeghi H (2010) The effects of different salinity levels on some important physiological characteristics of two wheat cultivars. 11th Iranian Crop Science Congress, Environmental Sciences research Institute, Shahid Beheshti University, Tehran, Iran
Salehifar M, Torang A, Farzanfar M, Salehifar M (2010) Comparison of salinity stress effect on germination and seedling growth in 8 lines genotypes of common bean (*Phaseolus vulgaris*). 11th Iranian Crop Science Congress, Environmental Sciences research Institute, Shahid Beheshti University, Tehra, Iran
Santos CV, IP F˜a, Pinto GC, Oliveira H, Loureiro J (2002) Nutrient responses and glutamate and proline metabolism in sunflower plants and calli under Na_2SO_4 stress. J Plant Nutr Soil Sci 165:366–372
Sarraf M (2004) Assessing the costs of environmental degradation in the Middle East and North Africa countries. Environment Strategy Notes, No. 9. Environment Department, World Bank, Washington, DC
Shirokova YI, Forkutsa I, Sharafutdinova N (2000) Use of electrical conductivity instead of soluble salts for soil salinity monitoring in Central Asia. Irrig Drain Syst 14:199–205
Shrivastava P, Kumar R (2015) Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi J Biol Sci 22(2):123–131
Sival AA, Skaggs TH, Van Genuchten MT (2009) Reclamation of saline soils by partial ponding: simulations for different soils. Vadose Zone J 9(2):486–495
Soil Survey Staff (1993) Soil Survey Manual, Handbook 18, USDA, NRCS. US Gov Print Off, Washington, DC

Sun Y, Li X, Mander U, He Y, Jia Y, Ma Z, Guo W, Xin Z (2011) Effect of reclamation time and land use on soil properties in Changjiang River Estuary, China. Chin Geogr Sci 21(4):403–416

Tester M, Davenport R (2003) Na^+ tolerance and Na^+ transport in higher plants. Ann Bot 91:503–527

Tobe K, Li X, Omasa K (2002) Effects of sodium, magnesium and calcium salts on seed germination and radicle survival of a halophyte, Kalidium capsicum (Chenopodiaceae). Australian. J Botany 50:163–169

Tobe K, Zhang L, Omasa K (2003) Alleviatory effects of calcium on the toxicity of sodium, potassium and magnesium chlorides to seed germination in three non- halophytes. Seed Sci Res 13:47–54

USDA NRCS (2010) Plants for saline to sodic soil conditions. Technical Note: Plant Materials 9A, USDA-NRCS, Salt Lake City, Utah

USDA-NRCS (2011) Crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (ECw) or soil salinity (ECe). USDA-NRCS, Washington, DC Gregory PJ, Nortcliff S (2012) Soil Conditions and Plant Growth. Blackwell-Wiley, London, UK

Van Breemen N, Burman P (2002) Soil formation, 2nd edn. Kluwer Academic Publishers, Dodrecht

Wang L, Coles N, Wu C, Wu J (2014) Effect of long-term reclamation on soil properties on a coastal plain, Southeast China. J Coast Res 30(4):661–669

Wilson C, Lesch SM, Grieve CM (2000) Growth stage modulates salinity tolerance of New Zealand spinach (*Tetragonia tetragonioides*, Pall) and Red Orach (*Atriplex hortensis* L). Annals Bot 85:501–509

Yadav S, Irfan M, Ahmad A, Hayat S (2011) Causes of salinity and plant manifestations to salt stress: a review. J Environ Biol 32:667–685

Yensen NP (2008) Halophyte uses for the twenty-first century. In: Khan MA, Weber DJ (eds) Ecophysiology of high salinity tolerant plants. Springer, Dordrecht

Zeinolabedin J (2012) The effects of salt stress on plant growth. Tech J Eng Appl Sci (TJEAS) 2(1):7–10

Zhu JK (2001) Plant salt tolerance. Trends Plant Sci 6(2):66–71